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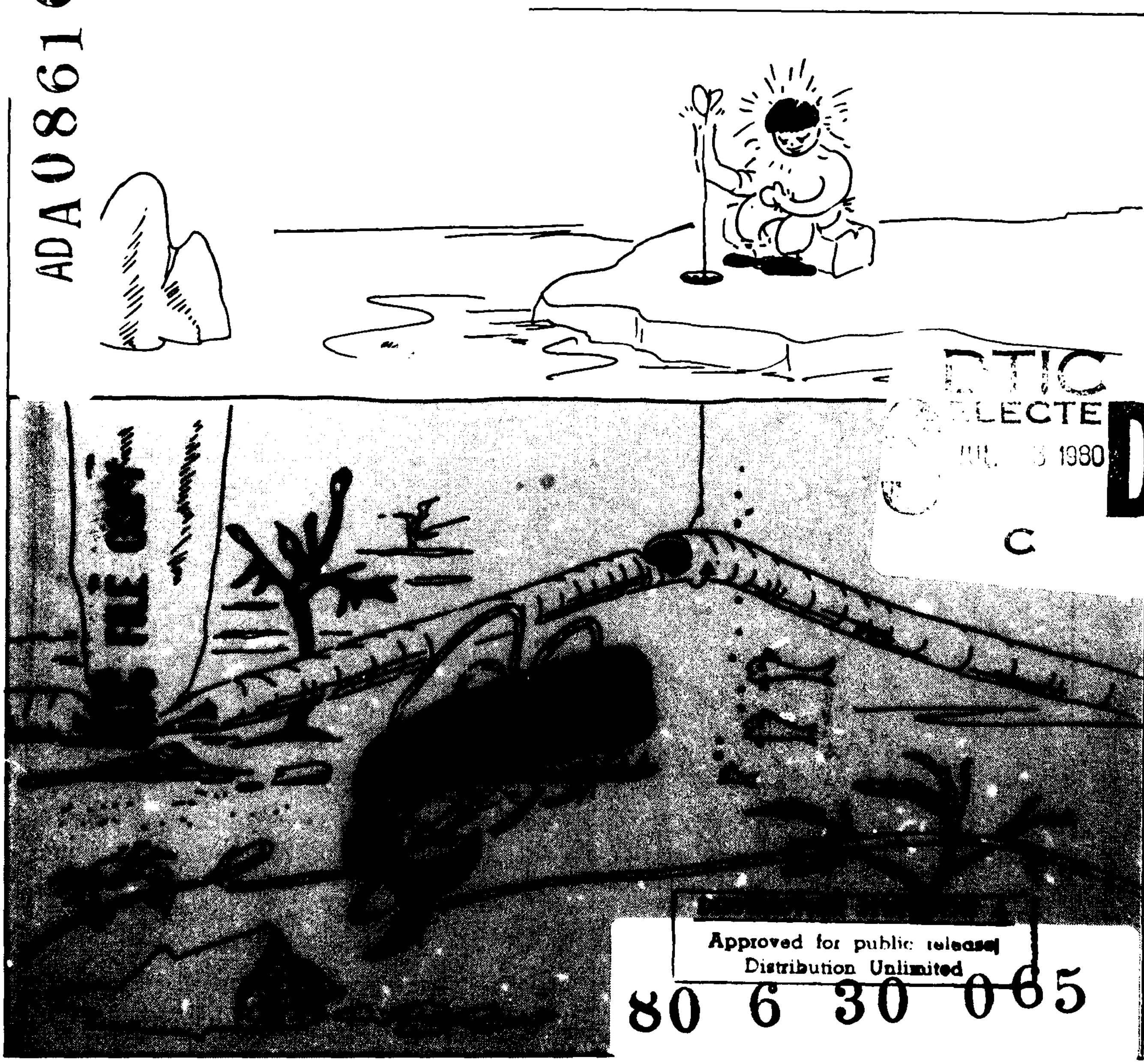

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Undersea pipelines and cables in polar waters

Malcolm Mellor

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Special environmental factors that influence the design, laying and maintenance of undersea pipelines and cables in polar waters are described. Various approaches to the protection of submarine pipes and cables are considered, and prime emphasis is given to burial techniques for shallow water. A wide range of methods for trenching and burying are discussed, and technical data are given.

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PREFACE

This report was prepared by Dr. Malcolm Mellor, Physical Scientist, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was funded under DA Project 4A161101A91D, *In-House Laboratory Independent Research*. The report was reviewed by Paul V. Sellmann and Dr. Ronald Liston of CRREL.

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These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4*	millimeter
foot	0.3048*	meter
foot/minute	0.00508*	meter/second
foot/second	0.3048*	meter/second
knot	0.5144444	meter/second
revolution/minute	0.1047	radian/second
pound force	4.448222	newton
pound force/inch^2	6894.757	newton/meter^2
pound force/foot^2	47.88026	pascal (N/m^2)
ton (short)	907.1847	kilogram
foot^3/minute	0.0004719474	meter^3/second
gallon/minute	0.00006309020	meter^3/second
horsepower	0.7457	kilowatt
foot^3/pound	0.06242	meter^3/kilogram
pound/foot	1.488	kilogram/meter

* Exact

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UNDERSEA PIPELINES AND CABLES IN POLAR WATERS

Malcolm Mellor

Introduction

Undersea pipelines and cables can easily be damaged if they are not properly protected, especially in shallow coastal waters. In the past, comparatively little effort was made to protect cables and pipelines, apart from warnings and anchoring prohibitions printed on nautical charts. With the proliferation of underwater pipelines and cables, it is clearly impractical to reserve the seabed over great areas, and in any case anchoring and trawling prohibitions provide no protection against natural hazards, or against deliberate hostile action.

Government regulations in various countries now call for the protection of pipelines and cables, usually by burial. However, even where such regulations exist, they are not always met or enforced because of expense and technical difficulties. In fact, some regulations are being relaxed in order to relieve industry of the more difficult burial tasks.

In polar waters, pipelines and cables can be exposed to most of the hazards that exist outside the polar regions, and in addition they can be threatened by special natural hazards that are peculiar to those waters. There are some areas of major significance where burial of pipes and cables is a matter of necessity, not of choice or convenience.

The technical problems of submarine burial in polar waters are at least as severe as those encountered elsewhere, but the consequences of failure are probably more serious. Since current capabilities are barely adequate for operations in the temperate regions, some trouble can be expected when large scale burying has to be done in the Arctic.

One of the major concerns in polar waters is floating ice, both true sea ice and freshwater icebergs calved from glaciers. Deep keels of pressure ridges or icebergs can gouge into the bottom sediments as the floating ice moves under the influence of wind and current. Large ice masses can also ground or settle on hard bottom, crushing cables or pipes that might lie there. In very shallow water, ice can adhere to the bottom or to objects lying on the bottom, but the ice may be moved by local thrusting or by tidal action.

Another feature of polar waters is subsea permafrost. In some areas the subsea permafrost is not ice-bonded, and for practical purposes it is not much different from unfrozen bottom material. However, there are other areas where the bottom sediments are bonded by ice, at least partially. Subsea permafrost is not expected to cause any insuperable excavation problems, but thermal problems and consequent pipeline stability problems are distinct possibilities, especially where there are transitions between bonded and unbonded bed materials.

On the other hand, there may be some advantages to be gained from sea ice and subsea permafrost. The sea ice provides a working platform for part of the year, and this can be used both for laying and burying. Partial ice-bonding in the subsea permafrost could improve sidewall

stability in a trench, thus reducing the amount of excavation that has to be done. Finally, environmental considerations might favor an underwater route over a sensitive tundra route.

The purpose of this review is to outline the environmental conditions that affect the laying and protecting of pipelines and cables, and to examine the technical problems that might arise. Special attention is given to burying techniques.

Types of pipelines and cables

Problems could arise with a variety of types of pipelines and cables. The following types might be kept in mind.

1. Oil feeder lines from offshore wellheads. These could exist in considerable numbers, with relatively short runs more or less at right angles to the coastline. Oil carried in the lines could be warm enough to melt marginal permafrost surrounding the pipe.

2. Gas feeder lines from offshore wellheads. Though broadly similar to oil feeder lines, these probably would not carry much heat.

3. Oil or gas trunk lines. In some parts of the Arctic, trunk lines will have to cross bays and make crossings between islands. In other areas, there may be an option of running a trunk line underwater parallel to the coastline to avoid the problems of overland pipelines on sensitive tundra. There is a significant distinction between oil and gas lines in terms of heat transfer characteristics, oil lines may tend to thaw permafrost, while gas lines could conceivably chill the sediments and cause heaving.

4. Public or military utilities. Local distribution systems for gas, water, or refined liquid fuels might include underwater runs.

5. Electric power cables. Power cables for civilian communities, military bases, or commercial undertakings might be laid underwater.

6. Telephone cables. Both local and "long line" telephone cables are likely to be laid under water.

7. Special purpose military/naval cables. Requirements exist for laying of special purpose cables in coastal waters, including arctic waters.

Potential hazards to pipelines and cables

Pipelines and cables laid under the sea are susceptible to damage by natural processes and by human activity. Examples of potential hazards that can exist almost anywhere include:

1. Wave and current action (buffeting, drag, scour, etc.)
2. Seismic disturbances
3. Turbidity currents, landslides, etc.
4. Ship anchors, especially when dragging
5. Fishing gear, especially heavy trawl boards
6. Hostile action and sabotage
7. Sea creatures (e.g. whales)

In arctic water a number of special hazards have to be added to the above list. They include:

8. Direct freeze contact with annual sea ice (in shallow water)
9. Bed gouging by ice keels
10. Ice crushing on hard bottom
11. Uncontrolled thaw of partially ice-bonded bed sediments
12. Frost heave from chilling of subsea marginal permafrost and unfrozen sediments
13. Frost action and ice thrust on beaches, bars and shoals
14. Pit scouring beneath flooded sea ice

Areas of concern

In this general review the intention is not to focus on any particular geographic area, except for the broad restriction to regions where ice and frozen soils are significant factors. However, there is an unavoidable tendency to emphasize certain places because they have been subjected to special scrutiny for one reason or another. To avoid unduly restrictive thinking, it should be kept in mind that potential problems exist in the following geographical areas.

1. Alaska: northern, western and southern coasts
2. Canada: western Arctic, Canadian Archipelago, and eastern coasts at least as far south as Labrador
3. Greenland: west coast, and possibly also east coast
4. Spitsbergen
5. Soviet Union: northern coast and adjacent islands, eastern and southeastern tip
6. Antarctica: McMurdo Sound a likely area for early concern

The main concern is with shallow coastal waters. The coastlines that have to be considered could include steep rocky coasts with deepwater inlets, stable skerry coastlines, flat-lying shallow water coasts with rapidly eroding shorelines, shifting beaches, river estuaries,

deltas, and even coasts that are permanently fringed with ice. The areas of concern could also include offshore islands, barrier islands, bars, shoals and so forth, as well as partially enclosed waters such as bays, fjords, inlets and lagoons. About the only things excluded are mangrove swamps and coral reefs.

Water depth

Where pipelines or cables traverse shipping lanes or fishing grounds, burial is desirable even in deep water. However, in most of the areas listed above there is relatively little ship activity, and the only special polar hazard in deep water is the possibility of a strike by the keel of a large iceberg. Thus the emphasis in this review is on shallow coastal waters, where the needs for protection are greatest and the range of applicable technology is broadest.

To establish some sort of limit, an arbitrary range of 0 to 40 m depth is taken. This is not intended to preclude the possibility of work at greater depths, but it gives some idea of the probable depth range for most projects. The following points were taken into consideration in setting a 40-m depth limit.

1. In the Beaufort Sea, ice gouging of the seabed is frequent and severe out to a water depth of 20 m, and there appears to be appreciable contemporary gouging out to about the 30-m water depth. Frequency of gouging seems to decrease with increasing water depth. Gouges have been found in water up to 80 m deep, but at this limit they are rare, and may well be relics of long ago. Keel depths of pressure ridges are commonly up to 20 m, and they can be as much as 50 m in exceptional cases. The ice shelves where ice islands originate are up to 60 m thick, but the small ice island fragments that move into coastal waters are usually only about 12 to 30 m thick.

2. Offshore drilling in sea ice areas is likely to be limited mainly to waters less than 20 m deep in the first phase of development. The drilling in Cook Inlet, Alaska, has generally been in water less than 20 m deep, and drilling in the western Canadian Arctic has been carried out from artificial islands built in water up to about 12 m deep. In the Canadian Arctic there have been applications for drilling in deeper waters, but objections have been raised on the grounds that this would be too hazardous at the present time (the situation could change with development of suitable drill ships, hover platforms, etc.).

3. Machines that transmit forces directly to the seabed, such as stinger plows, ladder dredges, or cutterhead boom dredges, can operate in water up to about 40 m deep. In deeper water it is easy to transmit power, but direct mechanical transmission of force is difficult.

4. Down to 40 m, zero decompression dives can be made with scuba or lightweight equipment for routine inspection, survey, control, adjustment and so on.

Sea ice

Sea ice is formed by the freezing of seawater, as distinct from icebergs and iceberg fragments that originate as glacier ice. The average salinity of seawater is 35 g of salts per kg of water, usually expressed as 35‰. Lower salinities occur in the surface waters of polar regions where there is dilution by meltwater or river outflows. The freezing point for salinity S can be estimated as $-0.055\ S$ °C, where S is in ‰; for $S = 35‰$ freezing begins at -1.9°C, and for $S = 30‰$ freezing begins at about -1.7°C.

Unlike fresh water, which reaches maximum density at $+4$°C, seawater of salinity $S > 24.7‰$ increases in density as it is cooled to the freezing point. Thus, under still conditions, slowly cooling surface water sinks and warmer water from below rises to the cooling surface. Under idealized conditions the entire water body would have to cool to the freezing point before ice formation could begin, but in reality rapid cooling can form ice at the surface before the deeper waters are completely isothermal at the freezing point. What may be of more consequence in the present context is that stable thermal stratification can exist, with the coldest water at the bottom.

When freezing begins, small crystals appear in the form of needles or platelets. As the floating crystals multiply, grow and agglomerate, a slush forms at the surface; as it thickens, the slush layer may break up into "pancakes" under the influence of gentle wave motion. Finally, the ice forms a continuous sheet, and further growth is controlled by heat conduction from the "warm" lower surface to the cold upper surface.

The initial crystals reject salts from their structure, tending to increase brine concentration at the ice/water interface. During subsequent growth and agglomeration of crystals, brine becomes trapped between ice lamellae and thus incorporated into crystals, and it is also trapped between crystals at the grain boundaries. The

amount of brine incorporated into the ice in this way depends largely on the rate of freezing, which decreases as the ice thickness increases. With very slow freezing the overall salinity of the ice can be as low as 2‰, and with very rapid freezing it can be as high as 20‰. The volume of liquid in the brine cells varies with temperature, since an equilibrium between salinity and freezing temperature has to be maintained. As the ice cools, certain salts tend to precipitate at particular temperatures, for example sodium sulfate decahydrate at −8°C and sodium chloride dihydrate at about −23°C.

One consequence of freeze/thaw fluctuations in brine pockets is that brine can diffuse down through a cold ice sheet under the combined influences of temperature gradient and gravity, leading to gradual decrease of salinity with time. This freshening process is speeded up greatly when brine pockets become big enough to interconnect and permit free drainage. Sea ice that has survived a summer season usually has very low residual salinity. Another consequence of brine volume fluctuation is a corresponding fluctuation of mechanical properties because of changes in porosity as the temperature varies (there is also an intrinsic temperature dependence in the matrix of pure ice).

The crystals in sea ice have preferred orientation with the optic axes (c-axes) horizontal. Recent studies suggest that there may also be a preferred direction of c-axes that correlates with the directions of ocean currents.

The growth rate of sea ice is controlled by the rate at which heat can be removed from the freezing surface. This in turn is determined by the temperature gradient and the thermal conductivity of the ice. As the ice thickens, the temperature gradient tends to decrease, and the growth rate falls off. Once the ice cover is well established, ice thickness correlates well with the sum of freezing degree-days since first ice formation; thickness is more or less proportional to the square root of the degree-day sum, in accordance with the classic Stefan solution to this heat transfer problem. A variety of empirical equations have been used to accommodate the difference between actual ice surface temperature and the air temperature on which degree-days are based. Most approximate to the parabolic form of the Stefan equation, and one well known relation (the Zubov equation) is a quadratic equation. Variations in the growth relation for different sites are caused mainly by snow cover, wind conditions, and solar radiation characteristics.

Coastlines in the Arctic and Antarctic typically accumulate from 3000 to 7000 freezing degree-days (Celsius) during the course of a winter, and the maximum ice growth for one season is typically in the range 1.5 to 2.5 m. Growth terminates when the surface heat balance reverses in springtime. The ice then decays by surface ablation, internal melting and brine drainage. If there is sufficient upward heat flux from the ocean, ice may also be lost by basal melting. Brine drainage leaves the porous ice mass relatively pure, and quite resistant to further melting when it is immersed in cold saline water.

At any stage in its life, sea ice can be broken up by wind and waves to form *ice floes* and *pack ice*. Pack ice is an accumulation of broken sea ice that moves under the influence of ocean currents and wind shear. Velocity gradients in a field of moving pack ice create both shear strains and strains that increase or decrease the packing density of the ice floes. Large strains and high strain rates occur when the general movement is impeded by proximity to coastlines, shallow water, or intact *fast ice*.

Severe compressive strains lead to the formation of *pressure ridges*, where local buckling, crushing and thrusting cause ice to pile up, and later freeze, into a massive structure. Ridges can also form under the combined action of compression and shear. New ridges formed in seasonal fast ice or in seasonal pack ice typically rise 1 or 2 meters above the general ice surface, but much higher ridges can form when thick sea ice is subjected to very high stresses (the highest free-floating ridge observed so far rose almost 13 m above the surface). The visible "sail" of a recently formed ridge represents only a minor part of the total ridge depth, typically about 20%, although it can range from 10% to 25%. Extremely high ridges, rising to 38 m or more above the surface, can form where the ice becomes grounded on the seabed. Sections of pressure ridges can easily survive through a summer, becoming subdued in external profile but gaining strength through brine drainage and infilling with refrozen meltwater. Old pressure ridges, which typically have about 25% of their thickness above the surface, represent the most massive and formidable ice that is common and widespread in the Arctic.

Broken pack ice and old pressure ridges often become incorporated into a new ice sheet with the onset of winter. New ice forms over the water between old floes and blocks, and grows much more quickly than the thick old ice to form a coherent ice cover.

Sea ice occurs in zones that have definite characteristics. Close to coastlines the seasonal ice cover is usually well anchored and it does not move significantly. The ice often remains intact throughout the winter, although it can be broken by storms in autumn or early winter. This is known as *fast ice*. In some favored locations the fast ice does not break out every summer, and it can become very thick if there is a net accumulation of snow. Beyond the fast ice, the ice cover breaks frequently and moves as pack ice with wind and current, often thrusting, rafting and buckling to form hummocks and ridges. The belt that separates the moving *pack ice* from the immobile fast ice is termed the *shear zone*. Narrow shear zones produce severe breaking and grinding of the ice, and a *shear ridge* is formed. In the landlocked arctic basin, large ice masses can persist for many years; they are repeatedly modified by melting and refreezing, and form part of the *polar pack ice* that is replenished by new ice formation in winter. Around much of Antarctica, the pack ice is free to diffuse out into the open ocean without being recycled as it is in the central Arctic.

In any given geographical area the sea ice conditions may vary from year to year, but there are broad characteristics that remain the same.

Icebergs and ice islands

Icebergs are massive bodies of ice broken off from glaciers. Some are produced by land-based glaciers that terminate in the sea, especially fast moving valley glaciers or ice streams. Others are produced by floating ice shelves, especially the major ice shelves of Antarctica (Ross, Filchner, Amery). They drift under the influence of wind and current and eventually decay by melting and mechanical breakup, often after lengthy groundings at some stage in the journey.

Various terms are used to describe different sizes and shapes of icebergs; most are unnecessary for present purposes, but some distinctions have to be made.

Icebergs calved from land-based glaciers in the Arctic typically have quite small horizontal dimensions, and abrupt vertical relief. When a glacier snout thrusts out into tidal water, the floating cantilever is flexed by tidal motion, and it can easily break when the length to thickness ratio is about 2. With uniform thickness and vertical sides, a glacier berg would float with 12% of its thickness above water, so that at least one horizontal dimension is likely to be less than 20 times the height. The floating terminus of a glacier is often crevassed by tensile strains, and crevasses carried over into an iceberg help to produce dramatic sculpturing.

Major icebergs calved from floating ice shelves are typically flat-topped, with large horizontal dimensions, although small fragments do break off from cliffs at the ice front. Ice shelves cover great expanses with little change in thickness and no vertical restraint, so that there is not much tendency for the kind of flexure that would produce small bergs. The wide, flat-topped bergs are termed *tabular icebergs*. The average density of Antarctic shelf ice tends to be relatively low, so that tabular bergs float with about 17% of the thickness above water. Typical total thickness of Antarctic tabular bergs is around 200 m, and horizontal dimensions of several kilometers are quite common. Some bergs are tens of kilometers long, and one exceptional berg was measured as 180 km long.

Tabular icebergs are occasionally encountered in the Arctic, although there is only one known ice shelf, the Ward Hunt Ice Shelf of Ellesmere Island. Some very small tabular icebergs may be calved from certain floating glacier tongues. Tabular icebergs in the Arctic Ocean are known as *ice islands*, and research stations have been maintained on a number of them. Early in their life cycle, ice islands can be up to about 500 km^2 in area; eventually they break up into large numbers of smaller fragments, but the designation "ice island" is retained even for fragments as small as 1000 m^2 in area. The large ice island T-3 was about 50 m thick, but small fragments may be only 20 m thick.

Most icebergs and ice islands in the Arctic are calved from ice that is in an area of net ablation, and bergs are thus composed almost entirely of hard impermeable ice. By contrast, most antarctic icebergs break off from ice shelves that are areas of net accumulation, even at the ice front. Thus antarctic tabular bergs consist of permeable packed snow ("firn") in their upper layers.

The flotation characteristics of icebergs are quite variable. A uniform slab of typical glacier ice floats in ordinary seawater with about seven-eighths (88%) of its thickness submerged. Typical antarctic shelf ice has lower average density and it floats with about five-sixths (83%) of its thickness submerged. However, small icebergs are not uniform slabs. Wave action at the waterline undercuts the ice cliffs, which fall and leave an underwater bulge beneath the wave terrace, allowing the berg to then ride higher in the water. This effect, which is readily calculable, permits small bergs to invade relatively shallow waters.

The general drift patterns of icebergs are quite well known. For example, ice islands in the North American sector of the Arctic Ocean drift in clockwise, roughly elliptical, paths on the Alaskan side of the Lomonosov Ridge, moving westerly through the Beaufort and Chukchi Seas before swinging northerly towards the Pole and finally moving south again towards Ellesmere Island. Bergs calved from the glaciers of west Greenland drift south in the Labrador Current and out into the North Atlantic. Antarctic bergs tend to spiral away from the continent, reaching 40° latitude in the South Atlantic and the Indian Ocean.

Submarine permafrost

The simplest and most unambiguous definition of permafrost is: "soil or rock at temperatures permanently below 0°C." This says nothing about the mechanical properties of permafrost — a pile of dry gravel has much the same properties whether the temperature is +1 or −1°C. However, more elaborate or restrictive definitions of the term *permafrost* tend to create confusion without really clarifying the properties of the material. In this report the simple definition will be adhered to, and qualifications will be made as required.

In ice-covered northern waters the sea temperature is generally below 0°C, since the freezing temperature of normal-salinity seawater is about −1.9°C (salinity variations can produce temperature variations from about −1 to −2.5°C). Thus seabed permafrost is widespread in the Arctic and Antarctic. This does not necessarily mean that bed sediments have mechanical properties that are significantly different from those prevailing in warmer waters. If the pore water of the bed material is saline and unfrozen, then there is no ice bonding.

In most areas the interface between water and bed can never be much colder than −1.9°C (in special circumstances brine enrichment during surface freezing can permit lower temperatures). This means that submarine permafrost is never exposed to the very low surface temperatures that are typical in winter over terrestrial permafrost. If ice-saturated freshwater permafrost were to be sealed in a membrane and taken to the arctic seabed it would be relatively weak because of the high temperature, and in the case of fine-grained soils, especially clays, some of the fresh water content would be unfrozen at −1.9°C. With the membrane removed, further gradual deterioration of the ice-bonding would be expected, by salt diffusion in impermeable material and more rapidly by infiltration and diffusion in permeable material.

The coastal waters of the Beaufort Sea north of Prudhoe Bay and Point Barrow apparently cover large areas of submarine permafrost that is at least partially ice-bonded, and of considerable depth. Here the coastal lands are very flat and low-lying, and the sea is encroaching over the land due to shoreline erosion and thaw settling. Measurements of shoreline retreat have given long-term mean rates from 0.7 to 3.5 m/yr, with short-term local rates as high as 30 m/yr (Hopkins et al. 1977). Thus deep terrestrial permafrost, with its various characteristic features, is being submerged. In shallow water near the eroding shoreline there has not been much degradation of the ice-bonded permafrost, since ice freezes to the bottom out to a depth of about 2 m, thus providing a conduction path between the bed and cold air during winter. As water depth and distance from shore increase, the upper limit of ice-bonded permafrost tends to become further below the seabed, although there is not necessarily a clear demarcation between bonded and unbonded bed material. In fine-grained soils that were originally saturated with freshwater ice there is probably only slow thawing, since seawater temperature remains below 0°C and brine diffusion into the soil is a slow process. By contrast, granular soils that were originally unsaturated and permeable are readily infiltrated with seawater, which can then reduce or destroy the ice bonding even though the soil temperature is below 0°C. The thaw bulbs that originally existed beneath lakes prior to submergence would be likely to remain thawed or to be modified by partial freezing and water migration. At the lower boundary of the

relict undersea permafrost (which can be more than 600 m below the seabed), geothermal heat flow is expected to be thawing the bonded material at rates of the order of 10 mm/yr

Beyond the 90-m water depth of the Alaskan shelf there is not expected to be any ice-bonded permafrost, since this contour marks the furthest extent of shoreline at the last sea level minimum

Offshore from steep or stable coastlines, ice-bonded permafrost would not normally be expected to occur, except under very shallow water where ice grounds or freezes to the bottom. However, there may be special circumstances that could permit local formation of ice-bonded submarine permafrost. For example, periodic outflows or avalanches of turbid fresh water might under-run the nearshore salt water, laying down sediments at a rapid rate with fresh or brackish water in the pores.

From what has been discovered so far in the Beaufort Sea, it appears that the top of ice-bonded submarine permafrost is commonly tens of meters below the seabed in relatively shallow water beyond the 2-m depth. Further out to sea in the deeper water, the top of bonded permafrost can be more than 100 m below the seabed. In the Mackenzie Delta and some other parts of the Canadian continental shelf, drilling records indicate that the top of bonded permafrost can be hundreds of meters below the bed, even under shallow water.

There are indications that a shallow layer at the seabed may become partly ice-bonded on a seasonal basis, perhaps because of seasonal changes in the basal water temperature.

At some drilling sites on the Alaskan shelf, deposits of over-consolidated clays and muds have been encountered. Perhaps the most convincing explanation for these occurrences is one which invokes freeze-thaw cycling during periods when migrating barrier islands passed over the sites.

Ice gouging

Much of the seabed off the northern shores of Alaska and western Canada has been subjected to widespread gouging by ice. The bed sediments are furrowed into distinctive patterns, and in some areas it seems likely that the upper levels of the sediment layer are completely reworked by furrowing every few decades. Gouges are also found in other coastal waters and shallow seas where there is heavy moving ice, and some have been detected in relatively deep water (up to 80 m)*.

Gouges in the seabed are made by the keels of ice pressure ridges, and to a lesser extent by the keels of ice island fragments. In deeper waters icebergs can presumably gouge the bed when they ground. In the Beaufort Sea, the ice bodies that form the gouging tools are gripped in the pack ice, which itself is pushed along by wind shear that acts over wide surface areas (with a fresh breeze, wind shear over ice could be in the range 0.1 to 0.4 N m², depending on wind speed and ice roughness)

The dimensions of gouges are related to the size and the draft of the ice bodies, to the water depth, to changes in water depth, and to the strength of the bed material. Furrows are commonly of the order of 1 m deep, with a tendency for maximum furrow depth to increase with water depth, or with the draft of the ice that makes the furrow (Fig 1). Maximum recorded furrow depths have been given as 5.5 m for the Alaskan Beaufort Sea, 4.5 m for the Chukchi Sea and 10 m for the Canadian Beaufort Sea* (Hopkins et al. 1977). The width of a furrow can range from less than 1 m to about 100 m, depending on the width of the keel that did the gouging. Widths are commonly 30 to 40 m. Frequency of furrows (number per unit width of transect) tends to decrease with increasing water depth, and there is an inverse correlation between frequency and furrow depth. Gouging seems to be very frequent and widespread in water less than 7 m deep, but the resulting furrows are typically less than 0.5 m deep and they tend to become obliterated by wave action (Kovacs 1972). In the Beaufort Sea, significant gouging seems to be most intense in a range of water depths from 10 to 20 m. This zone separates the land-fast sea ice from the freely moving pack ice, large pressure ridges form, and the water is shallow enough for them to ground frequently, forming furrows that are commonly more than 1 m deep. Spacing between furrows may be of the order of 100 m.

The directions of furrows are related to wind and current directions, with dominant patterns for an area reflecting the direction of local ice drift. Off the north coast of Alaska, the domi-

* This 10-m-deep gouge was under 75 m of water (Pelletier and Shearer 1972), and may have been a relic from earlier times (see Kovacs and Mellor 1974)

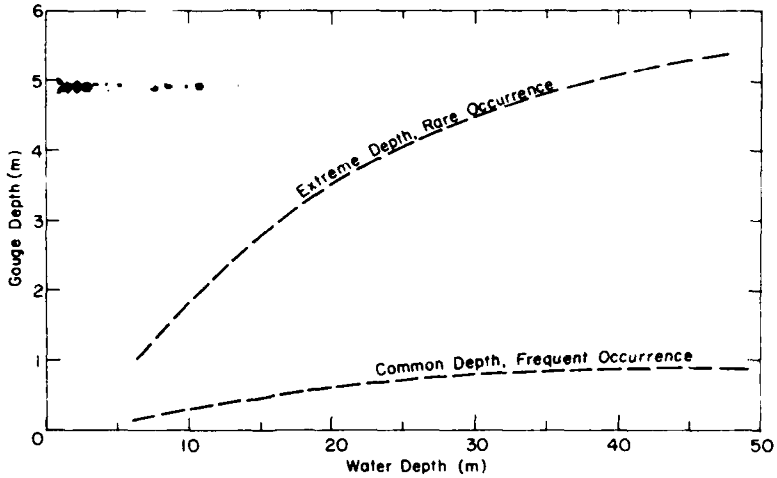

Figure 1. Simplified representation of ice gauge depth. Actual situations are complicated by local bathymetry, currents, ice characteristics, bed conditions, and so on.

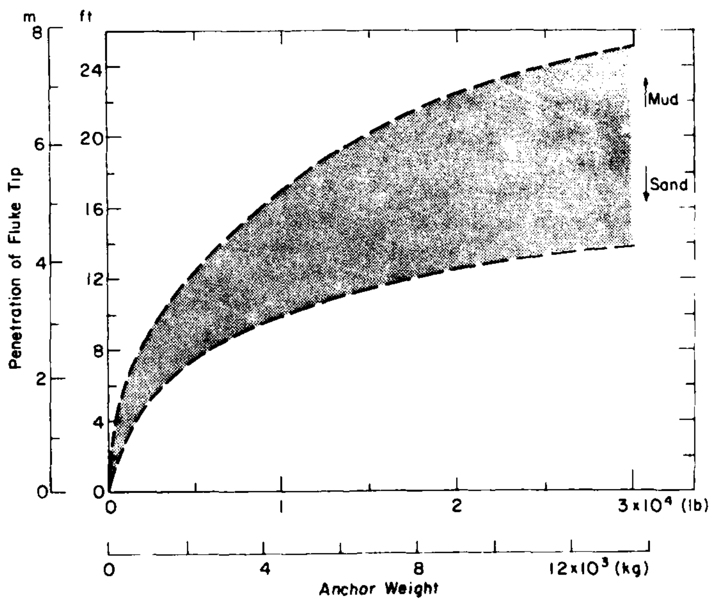

Figure 2. Penetration of anchor flukes in unfrozen bed sediments (data from Valent and Brackett, 1976).

nant direction is parallel to the coastline, with ice movement in a general westerly direction.

In some ways, ice gouging is comparable to the gouging that can result when a large anchor drags. Figure 2 gives an impression of the penetration depths for large anchors set in unfrozen sediments.

Seabed erosion by water jets

In the western Arctic, bed sediments under shallow water can be eroded by vertical water jets ejected from a flooded ice canopy. Heavy spring runoff from rivers (e.g. Mackenzie, Colville, Kuparuk, Putuligayuk, Sagavanirktok) can flood over the sea ice, causing it to be submerged to a depth of a meter or so. As the ice tries to rise under buoyant forces, water has to be transferred from above to below, and in an intact ice sheet there are seal holes and cracks to provide drains. Low pressure jets are thus formed, and sediments that are not too far below the ice can be jetted to form pits or trenches. The buoyant force gives a jet nozzle pressure of the order of 1.4 kN/m^2 (0.2 $lbf/in.^2$) and a nozzle velocity of about 1.7 m/s (5.5 ft/s). Power levels are low, but high flow rates can be achieved with sufficiently large holes (holes less than 2 ft in diameter give fractional horsepower and flow rates of a few thousand gallons per minute; above about 2 ft diameter, power levels exceed 1 hp and flow rates exceed 10,000 gal./min). The diameter of the jet determines the depth to which it can reach, and the diameter of the resulting scour pit. The limit of effective reach would not be expected to exceed about 10 nozzle diameters from the underside of the ice canopy.

Protection methods

Protection arrangements for undersea pipelines and cables fall into two broad categories: a) protection added to unburied lines, and b) burial of the lines.

Unburied lines can be protected in a variety of ways. One way is to lay line that has an armored sheath already fitted. Another method that is sometimes used to protect cable is to fit iron split-pipe around cable that is already layed. Another technique involves placing of heavy reinforced concrete covers over the line. Finally, there is the well proven method of placing a berm of rock fill over the line.

Burial can also be achieved in a variety of ways. One way is to excavate open trench and then lay the line into it. Alternatively, the line can be laid, and the trench excavated beneath it later. Another technique is direct plowing in during the course of the laying operation. In some circumstances it may be feasible to lay the line in a driven tunnel.

Protection of unburied pipes and cables

Unburied pipes and cables are protected by adding armor or cover that increases effective weight and strength (Fig. 3), and also tends to deflect anchors, trawl boards, and such like. This approach does not seem very appropriate for protecting against serious ice forces, but the main variants are listed below, and summarized in Figure 3.

1. Standard concrete weight coating on pipes. An annular ballast coat of unreinforced concrete, applied either by casting or guniting, provides protection against current action, and partial protection against some strikes.

2. Shaped weight coatings on pipes. Trapezoidal weight coatings of unreinforced concrete are used to minimize the effects of current forces. They can improve protection against minor strikes, and modifications might lead to further improvement of strike protection.

3. Concrete armor on pipes. It has been proposed (Brown 1972, 1973) that concrete pipe coatings might be made from high strength concrete or reinforced concrete.

4. Iron or steel armor. Cast iron split-pipe sections are fitted around existing cables for protection against wave and current action, both with and without rock anchors. It has been suggested that pipelines might be armored and ballasted by adding steel to the shell, without use of any concrete (cables are manufactured routinely with integral armor).

5. Reinforced concrete covers. Pipelines can be roofed over by laying sections of reinforced concrete on top of the pipe. The covers can be half-cylinders, arches, or flat-topped sections with sloping sides.

6. Rock berms. Rock berms have long been used to protect pipelines from wave action in surf zones, particularly at sewer outfalls. Undersea pipelines can be protected by using graded fill and riprap. Protection against anchors or against ice is improved by having gentle sideslopes and large riprap.

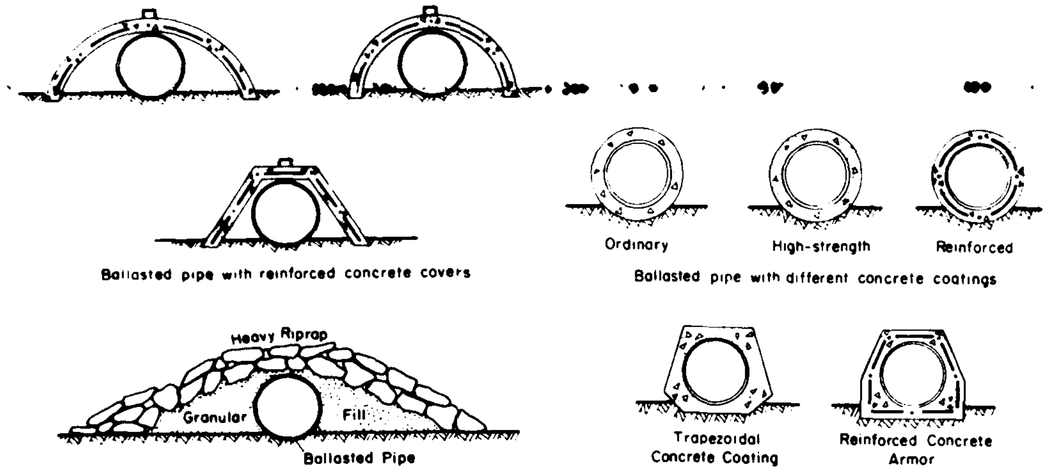

Figure 3 Protection arrangements for unburied underwater pipelines.

Protection by burial

It is generally conceded that burial provides the best protection against most of the hazards that threaten pipelines and cables, both on land and under the sea. With favorable soil conditions, burial may also be the most economical protection, but with hard bed conditions, burial can be prohibitively expensive using existing technology.

The following list gives the main techniques that might be considered for burying pipes and cables underwater.

1. Trenching with shovels or backhoes. Large backhoes and shovels are mounted on barges for digging and dredging in relatively shallow water. Experiments have also been made with a small backhoe mounted on an underwater bulldozer.

2. Trenching with draglines, clamshell grabs, and drop-tools. Buckets and other tools on cables can be used for digging and dredging in deeper water.

3. Plowing and ripping from surface vessels. Plows or rippers can be towed from the surface, either for the first stage of trench excavation or for direct burial of the pipeline or cable. Jets of water or air can be incorporated to enhance performance.

4. Plowing, ripping or blading from seabed machines. A number of experimental seabed vehicles with independent traction have been built, some specifically for excavation work.

5. Trenching with ladder dredges. Bucket-chain dredges of the kind used for harbor dredging or for gold and tin mining can be used for trenching in water that is not too deep.

6. Suction dredging. Simple suction dredges powered by surface pumps can be used to remove loose sediments in water that is not too deep. Capabilities can be enhanced by dragheads, jets, and booster pumps.

7. Trenching with conventional cutterhead dredges. Floating dredges with boom-mounted cutterheads and suction can be used in fairly shallow water.

8. Low pressure water jetting. Water jets operating with high flow rates at pressures up to about 20 MN/m^2 (3000 lbf/in.^{2}) are widely used for burial of pipelines and cables in water of any depth, provided the bed material is reasonably loose.

9. Bottom-traveling cutterhead dredges. Cutterhead machines that travel on the bed, either on an independent carriage or on the pipe itself, have been developed for pipe burying.

10. Explosive methods. Hard rock bed is usually broken with explosives before excavation. The chief methods are drill-and-blast, and shaped charges. Shaped charges and string shooting are sometimes employed for excavation of softer materials.

11. Novel methods. A variety of novel techniques are potentially applicable to undersea trenching. They range from simple hybrid modifications of well-tried devices, to truly exotic concepts requiring major development efforts.

Backhoe digging

Dipper dredges were formerly barge-mounted power face shovels of the cable-operated type. With cable equipment fast becoming obsolete, hydraulic backhoes mounted on barges are becoming accepted as perhaps the most versatile and effective dipper dredges.

A typical hydraulic backhoe has a boom ("upper arm"), a dipper arm ("forearm"), and a bucket or dipper ("hand"). There are three horizontal pivot axes: at the base of the boom ("shoulder"), at the junction of the boom and the dipper arm ("elbow"), and at the junction of the dipper arm and the dipper ("wrist"). Pivoting about the axes is forced by three sets of hydraulic actuators: the boom cylinders (typically a parallel pair), the dipper arm cylinder, and the dipper cylinder. Digging is accomplished by extending the arm, sweeping the dipper through an arc back towards the machine, lifting the loaded dipper, and swinging the entire machine about a vertical axis for dumping. Important characteristics are the horizontal reach, the vertical depth, and the lift height.

Backhoes are usually rated according to the maximum size of dipper, or bucket, that can be handled. Size is usually given in volume units as the *heaped capacity* of the bucket (which is greater than the actual volume, or *struck capacity*, of the bucket). Rated capacities of existing production machines range up to about 5 m^3 (6.5 yd^3). On any given machine, an extra large bucket can be used for easy digging in low density material, or a narrow bucket can be used for digging in tough materials.

Installed power ranges up to about 750 kW (1000 hp). Gross machine weight ranges up to about 135 tonnes (150 tons).

The maximum digging depth for standard machines ranges up to about 12 m (40 ft). However, dredging modifications have been made that increase the depth capability to about 17 m (57 ft). Depth is measured from the level of the machine's track pads to the working limit of the dipper teeth.

The cutting teeth set into the lip of a backhoe bucket can exert very high tangential forces,* especially when narrow buckets are used on large machines. With standard buckets, the force per unit width of bucket lip is in the range 120 to 200 N/mm (700 to 1100 lbf/in.). With narrow buckets, the force per unit width may be up to about 300 N/mm (1700 lbf/in.). Accounting for the usual spacing between teeth, the actual tooth forces are almost twice the values just given. Unit forces of this magnitude are high compared with typical forces exerted by high speed drag bits on large rotary drills, rock-cutting machines, and mining machines.

The short-term production rate of a backhoe working on land depends primarily on the digging conditions, the depth of cut, and the angle of swing. Digging conditions include the in-place strength and toughness of the ground, the density and bulking factor, and any other things that affect the rate at which ground can be disengaged and loaded into the dipper. Production rate decreases with increasing depth of cut, and with increasing angle of swing for the dumping part of the work cycle. The duration of one cycle is commonly about half a minute. Figure 4 gives some representative data for short-term production rates on dry land.

Ordinary tracked backhoes can work in shallow water without modification, provided that good maintenance procedures are followed to avoid bearing problems in the track system. In water that is more than a few feet deep at low tide, it becomes necessary to mount the backhoe on a barge, and to stabilize the barge with some system of legs, spuds or anchors. To achieve maximum digging depth with a given machine, the backhoe could be mounted in a well on its barge or pontoon. For underwater excavation the operator is usually digging "blind," although he can be aided by simple control indicators.

Large backhoe dredges should have no great difficulty in trenching submarine sediments, including those that are partially ice-bonded. On dry land, backhoes can dig some types of frozen ground without prior blasting. The frozen soils that can be dug by backhoes include marginally frozen materials at temperatures close to 0°C, soils with low ice content, and frozen layers that are underlain by unfrozen material. However, in compact soils that have high ice content, backhoes are not really effective at very low temperatures. In the so-called "TAPS tests" that were conducted in Alaska prior to construction of the first oil pipeline, a Koehring 505 heavy

* Cutting force terminology used here is consistent with that defined in a recent monograph on cutting tools (Mellor 1977). It may differ from terms used by backhoe manufacturers or operators.

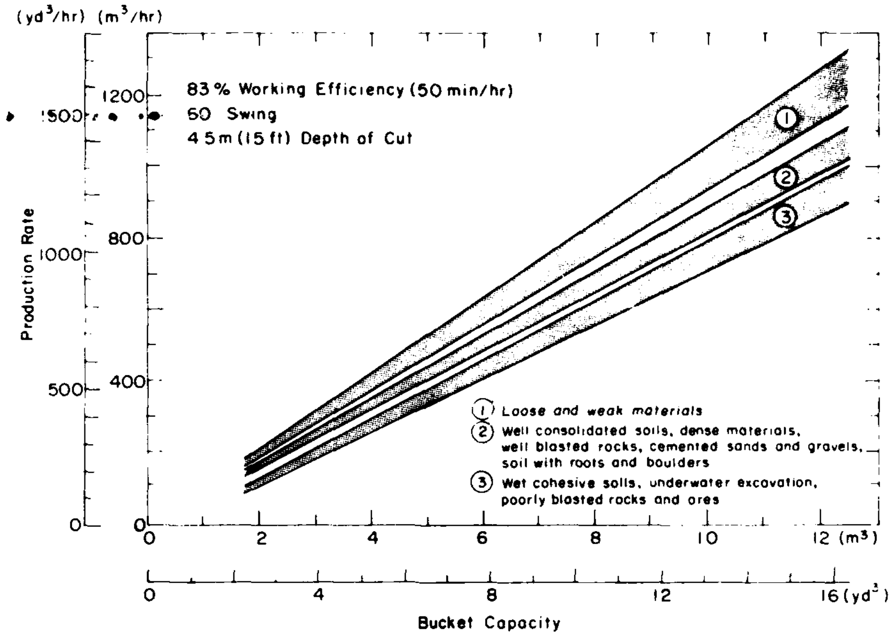

Figure 4. Production rates of hydraulic backhoes working in common materials on land (data taken largely from Koehring Estimating Manual).

backhoe was fitted with back-rippers and tested for trenching in frozen ground. It dug 7-ft-deep trench at a rate of 0.2 lineal feet per minute (0.06 m/min). In later tests sponsored by Koehring, the 505 dug frozen silt at rates up to 126 ft³/min (3.6 m³/min), and frozen gravel at rates up to 9 ft³/min (0.25 m³/min). These rates are extremely low compared to the rates attainable in loose and weak materials.

In recent years there have been a number of attempts to develop and introduce underwater bulldozers, which can also be fitted with backhoe attachments. The Komatsu underwater bulldozer was fitted with a backhoe and trenching tests were made. The machine dug ditch 1.0 m wide and 2.5 m deep in loose saturated sand; after slumping, the open trench was 2.3 m wide at the top and 1.9 m deep. The production rate was 35 m³/hr, or 46 yd³/hr (K. Furumi, personal communication).

Wireline equipment

There are several types of wireline devices that can be used for digging trenches. They include draglines (scraper dredges), clamshell grabs (grapple dredges), and special drop-tool ("orange peel") grabs. In principle, all can operate to very great depths, but control problems increase as the operating depth increases.

Conventional lattice-boom draglines are crawler-mounted cranes that "throw" a scraper bucket and fill it by dragging it back towards the machine. They are capable of long horizontal reach, but the depth for effective operation is limited. They work best in loose weak materials. Typical machines range in weight up to about 100,000 kg (220,000 lb), carry booms up to about 40 m (130 ft) long, and handle buckets up to about 5 m³ (6 yd³) in nominal capacity. There are, however, some gigantic draglines used in strip mining. The winching force of ordinary draglines ranges up to about 180 kN (40,000 lbf), and the maximum tooth force is up to about 100 N/mm (600 lbf/in.). Representative production rates for short-boom draglines working on land are given in Figure 5.

There are also fixed draglines that carry the bucket on a suspension cable. These are used for conveying material from a stockpile to a loading hopper.

A conventional lattice boom dragline is not suitable for digging in deep water, since the required pulling action cannot be provided. However, a dragline bucket carried on an anchored suspension cable could be used.

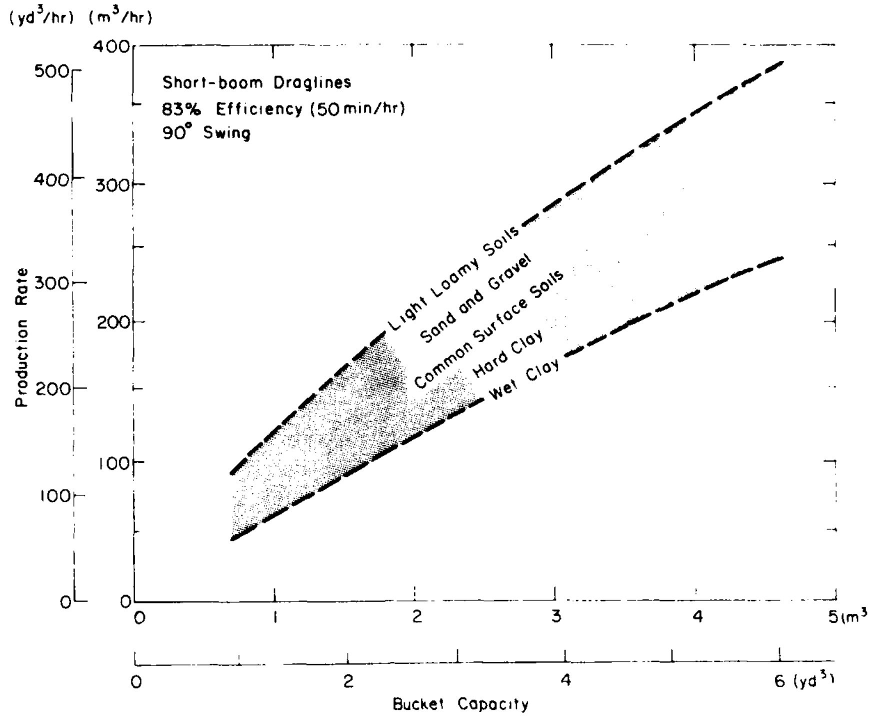

Figure 5. Production rates of short-boom draglines working in common materials on land (data taken largely from Koehring Estimating Manual).

Clamshell grabs are drop-buckets with hinged jaws. They are mounted on cranes in much the same way as dragline buckets. The bucket is dropped with the jaws open so as to penetrate the soil, the jaws are closed by an actuator cable, and the loaded bucket is hoisted and dumped. A simple clamshell has two jaws, but there are also more complicated devices that have several hinged segments. The latter type can be given a more aggressive attacking edge, making them useful for digging and shaft-sinking in tough materials. Grabs are widely used for digging and dredging in fairly deep water, and for work in restricted areas around marine structures. In shallow water, say 6 m (20 ft) deep, the production rate of a 1-yd^3 (0.76-m^3) grab bucket might be about 40 m^3/hr (50 yd^3/hr) in soft mud, and about 20 m^3/hr (25 yd^3/hr) in clay.

Grabs have limited capability for digging in weak rocks and blasted rock.

One of the factors that limits production rate in ordinary dredging work is the time taken to hoist the loaded grab. However, in underwater trenching it may not be necessary to lift the grab very far before swinging and dumping.

Plowing and ripping from the surface

Plowing is a standard method for burying cables, both on land and underwater. It is also used for pipe burial where pipe diameters are small, and plowing methods are being developed for burying pipes of large diameter. Ordinary plowing methods are usually confined to weak unbonded soils that are relatively easy to displace with a conventional moldboard. For breaking a furrow in strong soils and weak rocks, it is necessary to use a ripper, such as is fitted to heavy crawler tractors for hard ground excavation.

Plowing and ripping involve relatively high forces applied at low speeds, and various supplementary systems are used in attempts to reduce the horizontal force requirements. Soil plows can be made to vibrate, or they can be fitted with air jets or water jets. Heavy duty rippers have been fitted experimentally with gas-blasting nozzles, high pressure water jets, and percussive devices, but so far these auxiliary systems have not found general favor.

In plowing through soft soils, the main consideration is the horizontal force component,

which is usually much greater than the external vertical force component when the plow is designed to dig itself in. In ripping, and in plowing through strong soils, the applied vertical force is also an important consideration, since the horizontal and vertical components can be of comparable magnitude. Even under favorable conditions, the force levels for plowing can be formidable. Without getting involved in details of soil properties and plow designs, it seems that the horizontal force per unit area of the furrow cross-section is likely to be at least 10 lbf/in.^{2} (7 kN/m^2), and it could exceed 100 lbf/in.^{2} (70 kN/m^2). This translates to high force levels for furrows of useful dimensions, and there are difficulties in transmitting such forces from a surface vessel or surface platform.

Over the past 10 years, Bell Laboratories has developed a series of deep ocean cable plows for burying telephone cables in water depths to 3000 ft. These machines are sleds that carry an adjustable plowshare and feed shoe; telephone cable is picked up ahead of the machine and laid directly into the plowed trench. The sled is towed by a surface vessel, which also lays cable immediately ahead of the plow. The machines are all designated "Sea Plow." The first, built in 1966, was Sea Plow I, while the latest is Sea Plow IV. Sea Plow IV weighs close to 50,000 lbf (23 tonnes), and its furrow is 16 in. (0.4 m) wide by 24 in. (0.61 m) deep. Towing forces are said to be of the order of 50,000 lbf (23 tonnes), although they could on occasion approach 100,000 lbf (45 tonnes). These values are presumably for unconsolidated sediments typical of the deep ocean floor.

Simple estimates of underwater plowing forces based on soil properties have been made by Rockwell (1975), who considered a plow with 1-ft^2 (0.093-m^2) frontal area cutting to 3-ft (0.91-m) depth. He found that a towing force of 44,000 lbf (196 kN) was required in clay, and that 8000 lbf (36 kN) was required in cohesionless material. These values are in reasonable agreement with the Sea Plow forces.

Plowing usually takes place at low speeds, of the order of 1 knot (0.5 m/s), so that the power demand of the plow is not great. For example, a force of 100,000 lbf moving at 1 knot represents only 307 horsepower. However, screw-driven ships are very inefficient pulling devices, especially at low speed. Tugs that are optimized for pulling at relatively low speeds develop bollard pulls of 15 to 30 lbf/hp, so that the 100,000-lbf force moved at 1 knot would call for tug power of 3300 to 6700 hp.

Because force levels are high, and because conventional marine propulsion systems are inefficient for providing traction, there are incentives to reduce plowing forces and also to utilize more positive propulsion systems. Of the various possibilities for reducing plowing force, only water jets and air jets have so far found wide acceptance, although vibratory plowing has been adopted for cable burial on land. For propulsion, winching against anchors is an obvious expedient, and in special circumstances it may be possible to winch from the shore or from landfast sea ice.

A 10-in. gas pipeline was plowed-in beneath Turnagain Arm, near Anchorage, Alaska. The contractor built a plow designed to penetrate to a depth of 5 ft, with the trench about 3 ft wide. The face of the plow was drilled to provide jets of both water at 200 lbf/in.^{2} and air at 100 lbf/in.^{2}, presumably to assist in loosening and flushing the soil. The plow itself was mounted at the end of a 330-ft-long stinger boom, which permitted working in water up to 120 ft deep. The stinger was attached through a trunnion to a lay barge, which was about 250 ft long by 70 ft wide by 8 ft draft. The lay barge was winched forward to multiple anchors set by an attending tug, and additional side anchors were used to stabilize the barge against the tidal currents, which reached velocities as high as 7.6 knots. In the middle of the inlet, where the current scours the bottom down to the gravel layers, the plow was able to penetrate only 2 ft instead of the desired 5 ft.

Plowing from a surface vessel with the aid of a stinger or rigid towbar can be regarded as a proven technique. It is described in at least two patents.

Another jet plow was used in the Anchorage area to bury small diameter pipe in Cook Inlet. Brown & Root designed a plow that incorporated 300-lbf/in.^{2} jets, with a total flow rate of 3000 gal./min. There was also an air lift drawing 1500 ft^3/min. The plow was intended to have a maximum pulling force of 75,000 lbf.

Also in the Anchorage area, Chugach Electric Co. acquired a Harmstorf jet plow for burying cables beneath Knik Arm. The plow is carried by large wheels, which are actually steel cylinders, each 2 m in diameter and over 1.5 m wide. The Harmstorf Company of Hamburg, Germany, has

been developing and using jet plows for many years. Originally used for burying cables, some of the equipment can now handle flexible pipes up to almost 4 ft in diameter. Jet pressures are believed to be in the range 100 to 180 lbf/in.[2] A large crawler-mounted machine built in 1972 had a hydraulic output of 1450 hp, requiring an input driving power of 2500 hp for the pump.

Very recently, R.J. Brown and Associates built an underwater plow for cutting pipeline trench in the North Sea, and buried 2.2 km of 36-in. (0.91-m) diameter pipe in 165 m of water in the Statfjord Field. The plow is 12 m long and weighs 50 tons. The leading end is supported on rollers, and steel "disc harrows" serve as gauge cutters. The trench it cut was 2 m wide and 1.1 m deep, and the required 80 tons of pull was provided by a tug. R.J. Brown & Associates also plan to use a similar plow to bury a gas pipeline for Panarctic Oils Ltd. near Melville Island in the Canadian Arctic. For this job, the plow will be pulled by a winch set on the sea ice.

Plowing and ripping by self-propelled seabed vehicles

Self-propelled seabed vehicles of various kinds have been built and used, but at present they are not at a very advanced state of development. Nevertheless, they have certain attractions for underwater plowing and ripping, provided that adequate traction and vertical reaction can be provided.

Some idea of the required horizontal forces for plowing in soft materials has already been given. In round terms, practical plowing operations typically involve horizontal forces in the range 10,000 to 100,000 lbf for cable burial, and perhaps 100,000 to 200,000 lbf for burial of fairly large pipes. Underwater ripping has not been used to any significant extent, but if a conventional single-tooth tractor ripper were to be used in tough soils or rippable rock, the horizontal forces might be in the range 50,000 to 100,000 lbf, and the required vertical reaction on the ripper shank might be of the order of 30,000 lbf or more when starting a run.

COMEX has built and operated a self-propelled underwater crawler tractor that is fitted with a cable plow intended to bury cables up to 80 mm in diameter in trench that is 0.9 m deep and 0.1 mm wide. The tractor is electrohydraulic, and has no buoyancy tanks. Operators ferry to the tractor in a self-propelled lightweight two-man submersible vehicle, the "Globule." The Globule clips on to the tractor by electromagnetic connectors, and becomes the control cab for cable-trenching work. The plow is said to be capable of working in clay, and even in coral. The operating weight is 25 tonnes in air, and 16 tonnes underwater. The ground pressure is 0.16 kg/cm² submerged. The maximum drawbar pull underwater is not likely to exceed 13 tonnes (28,000 lbf) in good conditions (assuming adequate power).

An underwater tractor has also been built and subjected to operational testing by Komatsu Ltd. It is of conventional form for a construction tractor, but has electric drive and pressure-sealed bearings. The tractor can carry a variety of attachments, including a conventional three shank ripper capable of penetrating to a depth of 0.61 m (2 ft). The operating weight is 42,300 kg (93,250 lb) in air, and 30,800 kg (67,900 lb) submerged. This means that with adequate power the drawbar pull is not likely to exceed 50,000 lbf (23 tonnes) when running on bottom sediments. The ground pressure when submerged is 0.74 kgf/cm² (10.7 lbf/in.²), which is rather high for operation over soft materials. The installed power is 125 kW (168 hp), so that at 1 knot (0.51 m/s) the power also limits the possible drawbar pull to about 50,000 lbf (23 tonnes) when drive train losses are taken into account.

Another experimental underwater tractor has been built by Hitachi Ltd. This machine has buoyancy tanks, but no technical details are available to the writer.

While bottom-crawling plows and rippers appear attractive, there are substantial mobility problems. The first problem is traction, which has already been alluded to. For any given material, net traction (or drawbar pull) is more or less proportional to vehicle gross weight, and it would be wildly optimistic to expect net traction to be more than 80% of the vehicle gross weight unless bed conditions are extremely favorable. It would not be unrealistic to set the target as low as 30% of vehicle gross weight for operation over a range of bed sediments. This means that very heavy vehicles (possibly carrying lead ballast) would be needed to develop very high plowing forces, and of course the track bearing pressure would have to be kept within limits to prevent sinkage in soft bottom. The second major problem is obstacle negotiation in coastal waters where there is abrupt bottom relief. This

again tends to call for large vehicles, or for articulated machines. If the machine is required to rip across rough bottom (ordinary plowing would probably be out of the question on hard bottom), the ripper shank has to be stabilized in an approximately vertical plane.

Bucket ladder dredges

Bucket ladder dredges (or dredgers) are used 1) for maintaining and increasing the depth of navigation channels in harbors, rivers and approaches, 2) for producing sand and gravel from underwater deposits, and 3) placer mining of gold and tin. Most consist of a hull carrying a boom ("ladder") that can slide and pivot, in such a way that digging depth and ladder angle can be varied independently to some extent. A chain of buckets runs along the boom or ladder, with empty buckets descending on the lower side of the ladder, biting into the work as they pass around the lower tumbler, and ascending to the upper tumbler for dumping. Most have a single ladder, although double ladder types have been built.

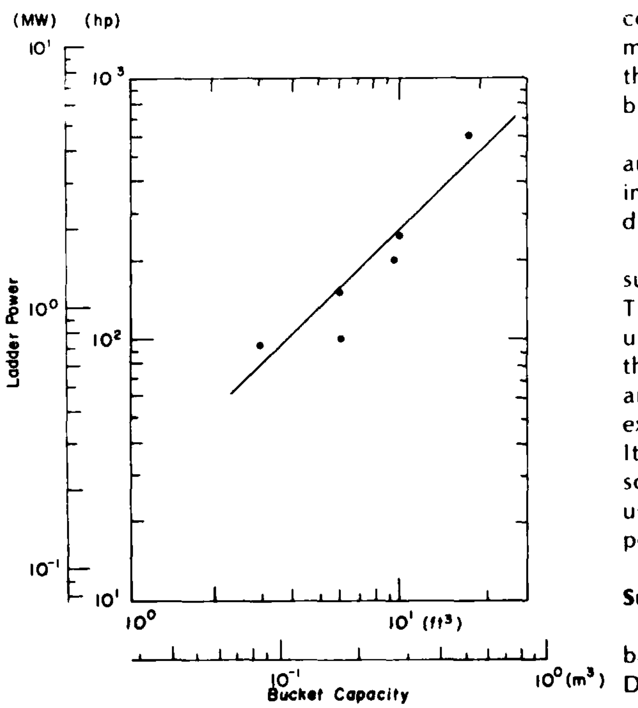

Figure 6. Ladder power as a function of bucket capacity for ladder dredges.

The size of a ladder dredge has traditionally been defined in terms of bucket capacity. The capacity of a single bucket is in the range 5 ft³ to over 50 ft³ (0.14 to over 1.4 m³), and maximum belt speed is in the range 20 to 30 buckets per minute, with a tendency for maximum speed to decrease with bucket capacity. The actual operating speed varies with the working conditions, maximum belt speeds are attainable in soft bottom material, but they may drop to around 10 buckets per minute in stiff clay and other tough materials. Maximum operating depths are commonly in the range 40 to 75 ft, but ladder dredges have reached depths up to 175 ft. Data on ladder power are not readily available to the writer, partly because the installed power on a ladder dredger is often much higher than the power actually used for digging, especially on mining dredges. However, a very rough idea is given by Figure 6, which indicates that something on the order of 30 hp per cubic foot of individual bucket capacity might be reasonable for a fairly high-powered dredge that can run its chain at 20 to 25 buckets per minute. In typical operations in soft material the buckets might fill to about 85% of capacity, but they could pick up less when chewing into tough material. Production rate can be estimated on the basis of bucket capacity, filling factor, and bucket speed.

Channel dredgers can work while stabilized by anchors, but they cannot tolerate high seas. Mining dredges are usually stabilized by spuds driven into the bed.

It is worth noting that gold dredges were used successfully in Alaska and the Yukon long ago. The permafrost in which they operated was usually thawed or softened by steam points, but they were capable of digging in bouldery gravels and weak bedrock that would still create serious excavation problems for small scale equipment. It is believed that dredges are used for large-scale permafrost excavation in the Soviet Union, using widespread flooding to create a dredge pond and thaw the ground.

Suction dredging

Suction dredging, or hydraulic dredging, is the basis of most modern dredging operations. Disturbed bottom material is sucked into a lift pipe as a slurry, with concentration of solids typically up to 20%, and transported to the surface, usually by centrifugal pumps. Some

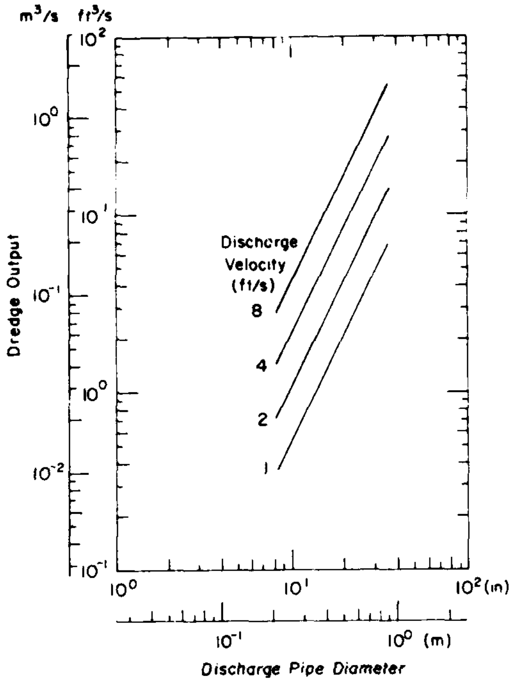

Figure 7. Approximate output of suction dredges as a function of pipe diameter and discharge velocity.

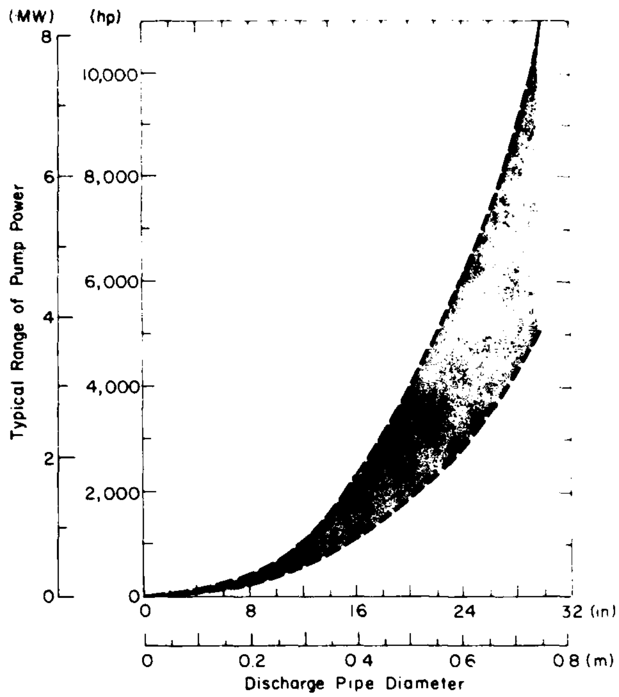

Figure 8. Typical range of pump power as a function of discharge pipe diameter for suction dredges.

dredges work by suction alone, like giant vacuum cleaners, but there is usually some kind of head designed to loosen the bottom material for transport. The major types are: a) dustpan or draghead dredges, which carry a broad suction head that may be equipped with teeth, scrapers, or jets, and b) cutterhead dredges, which carry a rotating mechanical cutter at the end of the suction pipe. Only the suction function will be dealt with in this section, and cutterheads will be treated separately.

The size of a suction dredge is usually denoted by the diameter of its discharge pipe, which can range from about 8 in. to 36 in. The product of discharge velocity and pipe cross-section area determines the output of the dredge (Fig. 7) * The useful output is reckoned in terms of the volume of solid material that is pumped, this can be estimated if the volume concentration of solids in the flow is known. The required pump power is proportional to the flow rate and the total head, and therefore it can vary within quite broad limits. Figure 8 gives a general impression of pump power as a function of pipe size for typical operations. Power demands increase for high rate dredging in unusually deep water, where booster pumps (centrifugal pumps or jet pumps) are needed. Although dredging

* Available data suggest that discharge velocity is typically in the range 1 to 4 ft/s. However, tables published by Huston (1970) give the range as 10 to 25 ft/s, which seems very high

tends to be a shallow water operation, sand and gravel may be pulled from water more than 100 ft deep, and in Europe there are vessels capable of working in water up to 230 ft deep

Conventional cutterhead dredges

The conventional floating cutterhead dredge is a suction dredge that has an axial-rotation cutting device mounted at the intake of the suction line. The suction line and the cutterhead are mounted on a pivoting boom known as a "ladder." The ladder assembly is carried by a barge, which supplies power and transfers the spoil to a discharge line. The barge is stabilized for working by spuds and/or anchors. The cutterhead dredge is highly versatile, being able to excavate tough deposits as well as loose sediments; cutterheads can dig clays, coarse gravels, coral, and weak rocks. Some cutterhead dredges are shallow draught vessels that can be disassembled for transport and/or custom modification.

The cutter typically consists of a set of spiral blades combined into a "basket" that rotates on the end of a propeller shaft. In general form it can be compared to the ripping booms and roadheading machines that are used in underground mining. The basket of a cutterhead may be of "closed nose" or "open nose" design, and it may be fitted with replaceable blade edges or cutting teeth. Another type of cutterhead, known as a "straight arm" cutter, combines a set of straight blades to form a frustum of a cone. Closed nose baskets are typically used for digging loose materials, while open nose baskets and straight arm cutters provide more aggressive action in hard materials.

Cutterheads are up to about 12 ft in diameter, and they rotate at 10 to 30 rpm, with bigger heads turning at lower speeds. Cutter power can range from a few hundred horsepower to more than 2000 hp. On older dredges, the head is turned by direct shaft drive from a geared electric motor on the barge. The shaft is carried inside the ladder in special cutless bearings. On new dredges, submerged hydraulic motors (or even electric motors) may be mounted near the cutting end of the ladder. Ladders range in length from about 25 ft to over 150 ft, and they are usually operated at angles up to about 45° from the horizontal.

A cutterhead dredge depends on both the suction function, which usually consumes most of the power, and the cutting function. However production rate tends to be set by the cutter. In very soft material, the production rate can be about 50% of the flow rate in the suction line whereas in hard soil it may be about 10% of the flow rate.

Low pressure water jetting

Low pressure water jets are widely used for burying undersea pipelines and cables in cohesionless bed materials. In this context, the term "low pressure" implies nozzle pressures up to about 3000 lbf/in², as distinct from the very high nozzle pressures (10,000 lbf/in² to more than 100,000 lbf/in²) that are used experimentally for rock-cutting. There are various ways of using low pressure jets, including the following:

1. Simple jets to dislodge and remove soil by blowing it away.
2. Simple jets to fluidize the soil beneath a heavy pipeline or cable.
3. Combinations of water jets and compressed air jets.
4. Jet disaggregators on the head of a suction dredge.
5. Jets added to mechanical plows.

Pure jet devices are carried on some kind of seabed vehicle. This can be a sled or carriage, traveling along a pipe or along the bed itself, or it can be a small submarine. The power demands for jetting are often very high, so that pumps and prime movers are usually carried on a surface vessel. In the pipeline industry, special "bury barges" are fitted out for jetting. The pressure capabilities of bury barges have tended to increase, from nozzle pressures originally around 300 lbf/in.² to pressures of 3000 lbf/in² on some new equipment. Some of the jets used for fluidizing loose soils under heavy pipes and cables can operate at very low pressures, down to about 20 lbf/in².

With large nozzle diameters and nozzle pressures above 1000 lbf/in², the power demands of a jet system can become quite large. Figure 9 shows the hydraulic power and the flow rate as functions of nozzle pressure for a range of nozzle diameters.

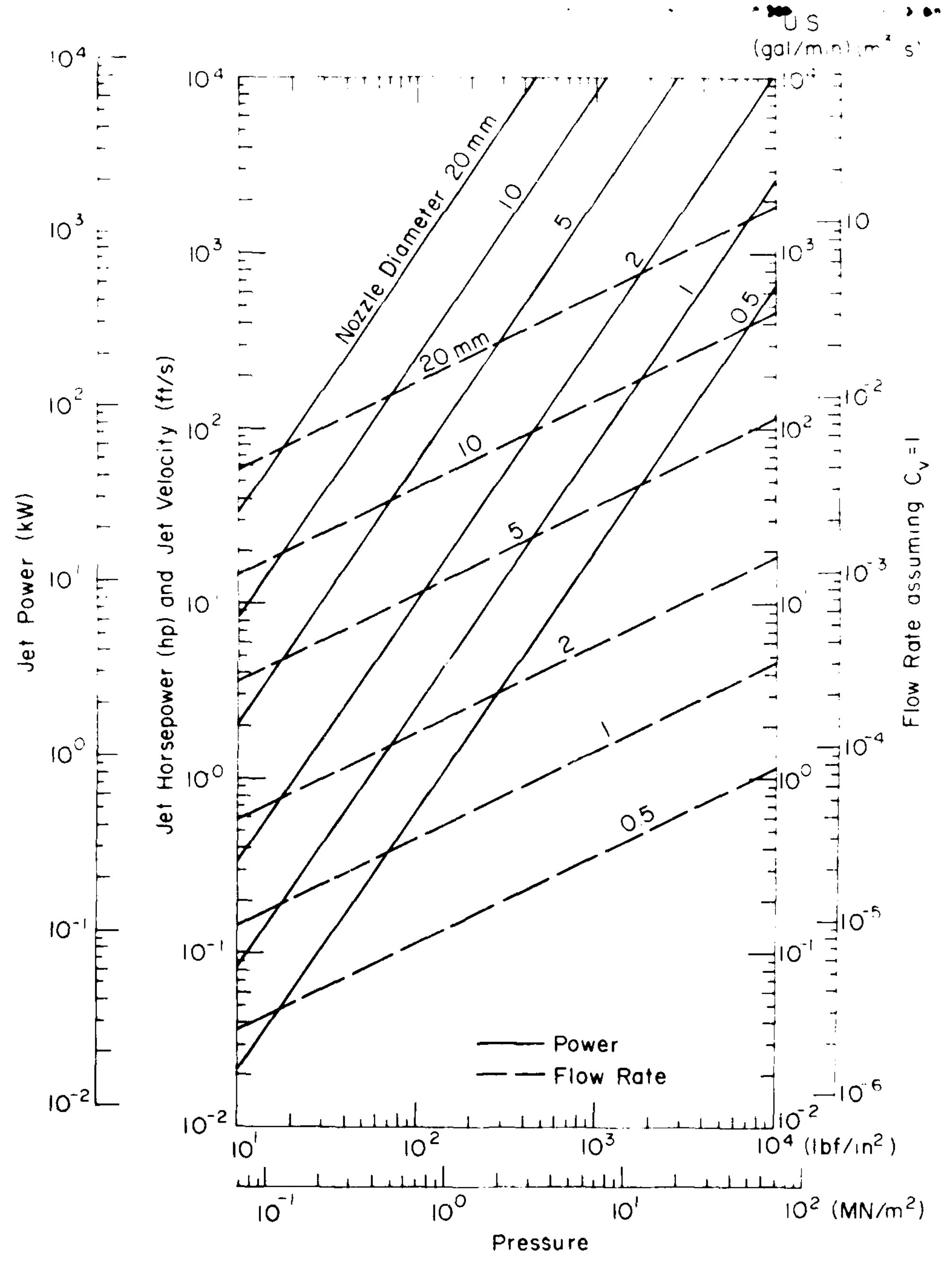

Figure 9. Hydraulic power and flow rate as functions of nozzle pressure and nozzle diameter for "low pressure" water jets.

Rockwell (1975) has examined the power requirements for actual jetting operations, and found that for each ft^3/min of excavation rate the required power level ranges from as little as 0.4 hp to an average upper limit of 11.6 hp. Putting these values in terms of specific energy, they translate as 92 to 2660 lbf/in^2, which does not seem particularly favorable in comparison with the specific energy for processes that employ direct mechanical attack.

With reference to bonded subsea permafrost, it might be mentioned that low pressure water jets were used for sluicing, or "hydraulicking," banks of frozen overburden during the heyday of Alaskan gold mining. Low pressure water jets were produced by firehose monitors under hydrostatic head. They were played on the overburden of the gold-bearing gravels, often against vertical faces, and the material was slowly cut away by a combination of melting and weak mechanical action. Slightly warmed water could presumably be used against subsea permafrost as a matter of expediency, although there is little that is inherently attractive about the idea for general use because of the low rates of working.

Bottom-traveling cutterhead dredges

Although conventional cutterhead dredges are effective and versatile machines, their operations are limited by water depth and by sea state. One solution to these problems is to use a cutterhead unit that travels on the seabed without a rigid connection to the surface vessel. The seabed vehicles that carry cutterheads are usually sleds or carriages that either ride the pipe or travel independently on the bed. They may be provided with controllable buoyancy to regulate the effective bearing pressure or to provide flotation for retrieval. Traction may be provided by crawler tracks or by cable tow, either from the surface or from kedge anchors.

Other approaches to the problem of wave motion are being studied in Europe. One idea is to have bottom-crawling structures with towers rising above the water surface. Another design that has recently been studied in detail by IHC Holland employs a large walking platform to carry a fairly conventional cutterhead ladder. Two connected pontoons are supported by four pairs of jackable legs that allow the platform to "walk" with 3-m steps in waters from 4 to 15 m deep. The 2000-hp cutterhead can sweep across a width of 65 m, and it is expected to be capable of tackling weak rocks.

A recent system intended strictly for pipe burial is the Kvaerner-Myren trenching system developed in Norway. A seabed unit designed for burying pipes at depths up to 500 m is operated from a 3000-ton mother ship. The 50-ton underwater unit has controlled-buoyancy spheres, and wheels for guiding it along the pipe. The cutterhead has a diameter of 5.9 ft, and it rotates about a vertical axis at 30 to 40 rpm. Projected trenching speeds are expected to be highest in clay (up to 500 m/hr), and less in sand. The umbilical is 750 m long. Although the developers do not mention it, a vertical axis slot miller of this kind will tend to veer off from the trenching line, since the cutter develops a force component normal to the direction of travel (this will be obvious to anyone who has used a router).

The problem of side force on a vertical-axis slot miller can be avoided by using a pair of contra-rotating cutters. An underwater pipe burying machine of this kind was the subject of a patent by C.F. Martin. This concept was developed by Oceanonics, Inc. into a working machine called the Mole, or Seamole. The original mole buried 16-in. pipe (23-in.-OD after coating) in clay (strength 200 lbf/ft^2) at a rate of 2 ft/min. The trench was 3 ft deep, 2 ft wide at the bottom, and 5 ft wide at the top. Cutter power was supplied by two 160-hp diesels, which suggests that the hydraulic motors were around 100 hp each. Maximum operating depth for the first model was 200 ft. A deep water version usable to 600 ft was later developed. This had a capability for burying 42-in. pipe. A prototype is said to have buried 12-in. pipe in Alaska, but reports are confusing and inconsistent ("North Slope," "25-ft tides"). This machine is said to have cut through frozen glacial till in the tidal flats, which seems unlikely.

A pipe-riding burial machine with twin cutterheads has also been developed by Sub Sea Oil Services (SSOS), a joint venture of Shell Italiana and Micoperi. This machine, the B70, has its cutters revolving about horizontal axes that point in the direction of travel. Driven by a 10-hp hydraulic motor, the cutters will handle soils, but they cannot cope with debris or hardwood.

There are several machines, or conceptual designs, that use a cutterhead on a swinging arm.

SSOS has a large swinging boom cutterhead trencher, designated the S/23. This machine is 59 ft long, with a weight of 50 tons submerged and 61 tons in air. It has variable buoyancy, and

travels on the seabed by winching two cables from anchor points. It is designed for cutting very large trenches — 9.1 to 14.75 ft wide, 0 to 8.25 ft deep per pass. The operating water depth limit is 200 ft. The operator's capsule and the machine room are maintained dry at surface atmospheric pressure. Power is electrohydraulic. The cutterhead is supplied by a 60-hp electric motor which drives a hydraulic pump and hydraulic motor (usable head power is therefore probably about 40 hp).

A swinging boom cutterhead mounted on self-propelled crawler tracks was built under sponsorship from the Japan Society for the Promotion of the Machinery Industry. The machine weighs 66 tons in air (55 tons submerged), its overall length is 38 ft, and its total width is 16.4 ft. The cutter diameter is 2.3 ft, and it has a 30 hp electrohydraulic drive. Maximum trenching width is 26 ft, and maximum trenching depth is almost 10 ft. Submerged bearing pressure of the 150-hp electrohydraulic crawler tracks is 10.7 lbf/in.^{2}. The machine, which is intended to dredge sand and clay, has sophisticated systems for control, guidance and monitoring.

Another self-propelled crawler with an articulated cutterhead dredge boom was designed in France by Groupement EPM on behalf of several companies and a government agency. A complete machine has not yet been built. This machine, known as the Tango, was intended initially for cutting trench 7.5 ft deep in water depths up to 500 ft. Maximum pipe diameter was expected to be 44 in. Overall length of the machine is 70 ft, total width is 27 ft, and the weight in air is 185 metric tons (204 short tons). There is provision for adjustable buoyancy, but planned track weight in water is 40 metric tons (44 short tons). Cutter power is 360 hp, crawler power is 130 hp, pump power is 360 hp and jet power is 180 hp, for a total of 1030 hp. Drives are electrohydraulic with line supply at 5.5 kV. Design progress rates are 360 ft/hr in sand and 160 ft/hr in clay. The cutterhead is 5.9 ft in diameter and 3.9 ft long. Control by an operator inside a dry capsule is planned for the first machine.

A large twin boom cutterhead crawler has actually been built and operated by Technomare in Venice. This machine, the TM-102, is 72 ft long with its booms extended, and 46 ft long with them folded. Total width is 39 ft. Total weight in air is 190 metric tons (209 short tons), and the machine has full adjustable buoyancy. Maximum submerged weight on the crawler tracks is 30 metric tons. Maximum size of pipe that can be buried is 5.25 ft, and maximum digging depth is 13 ft. Maximum soil strength for effective operation is 700 lbf/in.^{2}, and maximum water depth is 650 ft. Drive systems are electrohydraulic, with 3-kV line power supplied by a 1300-hp diesel-electric plant on the surface vessel.

Another machine built in Italy was the Saipem "Ponga," a submersible cutterhead dredge with four inclined-axis milling drums. It was intended for burying pipes up to 60 in. diameter in water depths to 200 ft (with provision for extension to 500 ft). The design was considered by this writer for possible application to arctic problems.

The machine consists of a 40- × 26- × 26-ft towed sled fitted with four cutter drums, each driven by 80-hp hydraulic motors. The sled straddles the pipe, and the drums cut the trench profile, while cuttings are flushed and fluidized by water jets. Fluidized cuttings are sucked away to the lay barge above by four 800-hp pumps. Power transmission is direct hydraulic.

Estimated excavation capacity is 315 to 360 ft^3/min. During tests in stiff clay (shear strength 2,500 lbf/ft^2, or 17.4 lbf/in.^{2}) the machine cut trench at 3.5 ft/min, with a cross section 12 ft wide at the top, 6 ft wide at the bottom, and a depth of 8 ft. This gives an actual excavation rate of 252 ft^3/min. If it is assumed that the hydraulic motors on the cutter drums were developing full power, the specific energy consumption for cutting (excluding fluidization and removal of cuttings) was 291 lbf/in.^{2}. While this appears to be a favorably low value when compared with some of the values quoted for various devices working in permafrost, it should be related to the strength of the material being cut. By this token the cutting performance of the Ponga is not impressive: the dimensionless performance index, for what it is worth in this case, is 8.4, which means that the machine is about 30 times less efficient than a good modern mining or tunneling machine. However, this is probably not of much concern when the pumps of the suction dredge account for ten times as much power as the cutter motors.

In considering the Ponga in relation to arctic conditions, it might be kept in mind that frozen gravel at −2°C could be about 25 times stronger than the clay for which the Ponga was designed,

but this does not necessarily mean that such designs could not be adapted for the Arctic — much of the submarine permafrost is probably only weakly bonded, or perhaps not bonded at all near the water interface.

The Demag Company of Duisburg produced a design for a seabed miner that was supposed to be usable for trenching. The crawler unit was intended to operate at water depths down to 16,000 ft, and most of the machinery was to be enclosed in a pressure hull. For trenching, the machine would have a cutterhead mounted on a slewing boom 33 to 50 ft long, permitting excavation across a 65-ft swath.

In 1970 the Northrop Corporation made a design study for a seabed excavator on behalf of the U.S. Navy Civil Engineering Laboratory. The machine was intended to excavate at rates up to 25 yd^3/min at water depths up to 6000 ft. All-aluminum construction kept weight to 30,000 lbf. The running gear consisted of two Sno Cat pontoons (the original open-ladder type) with a bearing pressure of 0.3 lbf/in.^{2}. The excavating function was performed by a cutterhead dredge on an articulated boom. Drives were all electric, with 5 hp going to the cutterhead, 17 hp going to traction, and a total installed power for all functions of 54 hp. The vehicle was 25 ft long by 20 ft wide, with an overall machine length (boom folded) of 49.5 ft. Supply line voltage was 2.4 kV. It is instructive to compare this feeble design with the brutes that have actually been put to work by ocean engineering companies.

In the mining industry there are various boom-mounted rotary cutters, known as roadheaders, that are used for driving tunnels. One common type, known as a "PK3 type" after the Russian machine from which it derives, has a conical cutter rotating axially at the end of a slewing boom. The general form of the machine is very similar to a cutterhead dredge, and to the bottom-traveling variants of cutterhead dredges. It could obviously be adapted to a hard bottom cutterhead. Another type of roadheader has a cutter drum that rotates about an axis that is normal to the boom axis. There are also roadheaders with two or more cutting drums, or with cutting drums that traverse along a rotating beam. These machines have been modified for civil engineering use, mainly for driving tunnels through the weaker kinds of rock.

Explosive methods

Explosives provide the standard expedient for breaking rock that is too strong for excavation by continuous cutting. The practical technology is well developed, and available for immediate application.

Conventional explosive methods for trenching involve the basic "drill-blast-muck" cycle whether the work is on land or under the sea. There are two general approaches. One relies on the drilling of small diameter shotholes in a pattern such as parallel lines with paired holes or with a staggered middle line ("5-spot"). The other is based on crater blasting, with a single row of charges set in shotholes of relatively large diameter.

Shotholes have to be drilled to at least the required trench depth and probably a foot or so deeper. Small diameter holes can be drilled underwater with hand-held diver tools, but for sustained production more substantial machines are needed. Conventional track-mounted pneumatic drills have been used successfully to drill small diameter holes for undersea work, although special modifications or procedures are necessary. The U.S. Navy Civil Engineering Laboratory has modified a conventional Worthington percussive rock drill to provide corrosion protection, sealing of bearings, hydraulics and pneumatics, and high visibility. In the U.K., a conventional Ingersoll-Rand percussive drill has been used successfully without modification by relying on scrupulous preventive maintenance after every working shift. In shallow water, drilling is often done from the surface, using barges or platforms that have extendable legs. A surface system would probably be needed to provide large diameter holes (6 in. or bigger) for crater blasting with cheap bulk explosives.*

Hole stability is a problem in underwater work. In soft materials or friable rocks, holes need to be cased or to be loaded immediately to avoid loss by slumping or blockage.

Small diameter holes (2 in. or less) would usually be loaded by hand with traditional solid explosives, such as dynamite, or equivalent

* One possibility for frugal crater blasting is spring hole loading. A small diameter hole is drilled, and a camouflet chamber is blasted at its base with a small charge. The chamber is then loaded with liquid or slurry explosive to provide a cratering charge. Design data are available.

modern cartridges. Special packaging of cartridges might be desirable, especially if delay deck charges were to be used. All-electric initiation of a multiple hole round can produce a jungle of leg wires, so that non-electric methods might well be preferable. With closely spaced holes underwater, there is a strong possibility of "flashover." Misfires are also common, and some blasters double the charge weight to compensate for possible misfires.

Large diameter holes can be loaded with water-resistant bulk explosive using some kind of mechanical charger. However, diver control would probably still be necessary. With a row of single crater charges there will usually be a large amount of overbreak to the sides of the row, but unbroken humps may be left along the bottom between shot points.

Required charge weights for trench blasting on land can be estimated for a wide range of materials,* but comparable estimation for underwater work is still a black art. One rule of thumb used in Europe calls for the dry-land charge weight to be increased by 1% for each 1 m of water depth. However, the usual expedient is to determine loadings on site by trial and error. For blasting row craters, the simple cube root scaling that is so successful for small scale work on dry land may not work too well, as gravity body forces are highly significant underwater.

Some companies (or agencies) from time to time promote the idea of using explosives to both break the ground and expel the broken material. This procedure is usually given some jazzy name like "blow and go." It seems unlikely that such a procedure would produce consistently satisfactory results underwater, so that provision has to be made for cleaning out the blasted trench.

On land, blasted trenches are usually mucked out with a backhoe, and in shallow water a similar operation might be feasible. In deep water, mechanical removal of blasted rock could be awkward unless there is good fragmentation. With good fragmentation, a suction dredge, eductor, or air-lift might be usable.

*Crater blasting and bench blasting on dry land can yield 10 to 60 ft^3 of breakage per pound of explosive under optimum conditions. However, for trench blasting in rock, much *heavier loads are commonly used and yield might be in the* range 4 to 20 ft^3/lb. For underwater row craters, yields of 3 to 7 ft^3/lb have been obtained in hard rock.

Shallow pipeline ditches under rivers are sometimes blown in soft materials or weak rocks by charges attached to a cable and laid directly on the bed. This is referred to as string shooting. There are various rules of thumb for string shooting, some expressed in odd forms. One that has been widely used can be boiled down to an expression for charge weight per unit length as kd^2, where d is water depth. With unit charge weight in lb/ft and d in feet, k is in the range 0.043 to 0.086.

A variant of string shooting employs a continuous hose charge or a series of long sausage charges. This variant is more practical and economical now that cheap sensitized slurry explosives are readily available.

Shooting at zero depth of burial is extremely inefficient in air (as much as an order of magnitude less efficient than optimum depth shots). Confinement by water ought to improve the situation, at least for soft materials, but the gas bubble (which represents most of the explosive energy) will still be unable to do much work on hard rock.

The other way to avoid the need for shothole drilling is to use shaped charges, either the usual radially symmetrical charges or linear shaped charges.

Shaped charges provide the standard military expedient for penetrating concrete, rock, steel and hard ground. They have not so far found wide industrial application, except for a few special jobs such as tapping blast furnaces, piercing well casings, etc. However, shaped charges have been used to provide shotholes in underwater blasting operations where divers are used. They have also been used in large numbers to shoot underwater trench, using special frames to lower and position the charges.

The standard conical shaped charge forms a jet by shock wave interaction and thus penetrates hard materials (this is known as the Monroe effect). The jet pressure far exceeds the yield stress of any material, and it carries along with it the metal of the core liner, both in the form of a spray of metal particles and in the form of a central "slug." The largest shaped charge in normal military use is the M3, which is nominally 40 lb and actually contains 30 lb of explosive. For civil use, shaped charges have been made by pouring liquid explosive (e.g. sensitized nitromethane) or sensitized slurry explosive into pressed steel cans, e.g. 15 lb of ex-

plosive in a 9-in.-diameter can. For greater safety, two-component explosives can be employed (non-explosive constituents are combined during loading).

Shaped charges have been tested systematically in frozen ground, and the results have been analyzed. For geometrically similar charges, linear dimensions of the pentration hole can be taken as proportional to either the cone diameter or the cube root of charge weight (assuming reasonably constant explosive density). With charges of conventional proportions, penetration in frozen ground is approximately 10 times the cone diameter, or about 2.7 $W^{1/3}$ ft, where W is weight of explosive filling in lb. With a 60° cone, the average hole diameter is about 60% of the cone diameter.

For use underwater, the performance of shaped charges should not be reduced very much in shallow water, although the hole may not always scour out quite as effectively. Shaped charges alone can produce underwater trench if used in sufficient numbers, and they can also be used to punch shotholes.

Flexible linear shaped charge has been developed for cutting purposes in the past few years. This material is flexible explosive strip with a V-groove moulded in its base (linear shaped charge can also be improvised by moulding plastic explosive over suitable "angle iron").

It is easy to see how linear shaped charges could be scaled up by filling casings of extruded metal or plastic with liquid or slurried explosive. A rough performance estimate for permafrost can be made on the basis of data for conventional shaped charges, e.g. by assuming that penetration will be roughly 10 times the charge width. In order to punch slot to a depth of 12 ft, the required charge width would be about 14.5 in. Making a guess about the charge cross section (similar to that for conventional 60° cone), and assuming an explosive specific gravity of 1.3, the approximate load would be 51 lb per lineal foot. The average slot width might be about 9 in. A rough check on the validity of this estimate can be made on the basis of specific energy: for the proposed linear shaped charge the specific energy is about 55,000 lbf/in.^{2} (assuming 1 kcal/g for the heat of explosion), whereas the specific energy for a conventional shaped charge in frozen ground is about 170,000 lbf/in.^{2} Thus the specific energy for the proposed load is three times lower (more optimistic) than the specific energy of conventional shaped charges. Surface to volume ratio for the slot is also three times lower than for the slender hole.

Another unconventional possibility in the explosive area is gas blasting.

Gas blasting devices give an abrupt discharge of gas or vapor, usually with initial release pressures in the range 10,000 to 20,000 lbf/in.^{2} (explosive detonation pressures are of the order of 10^6 lbf/in.^{2}). The small expansion between the initial discharge point and the confining medium is sufficient to drop the gas pressure below the yield stress of most materials, and there is virtually no shock wave generated by the gas release. Thus all the blasting action has to be achieved by gas expansion.

There are two well-established commercial gas blasting systems: airblast systems and compressed carbon dioxide systems. In the airblasting (Airdox) system a multi-stage compressor charges a bank of receivers, and high pressure air is discharged abruptly from a special shell when a pre-set pressure level is reached. With the CO_2 (Cardox) system, self-contained shells carry liquid carbon dioxide, which is abruptly vaporized and released through a rupturing membrane when an internal heater unit is fired electrically. There are also experimental systems that employ deflagration of gaseous fuel-oxidant mixtures. One developed for excavation was known originally as RED-SOD; it fires a compressed air/propane mixture in a combustion chamber, discharging gas through a venting port.

The airblast and CO_2 systems have been tested for breaking frozen ground, with apparently conflicting results. The first series of tests, which investigated both surface excavation and tunnel excavation, gave very good results and amazingly low values of specific energy (down to 50 lbf/in.^{2}, i.e. an order of magnitude more efficient than chemical explosives). However, these results may reflect skillful exploitation of prevailing conditions, which perhaps included an unfrozen or permeable sublayer in the case of surface excavation. The writer's personal experience is that compressed gas shells are incapable of breaking well-cemented ice-rich frozen soils with a useful burden when they are used under realistic practical conditions.

For some special applications, e.g. for heaving surface slabs, gas blasting is very attractive, and

the rapid-firing repetitive blast system (REDSOD) is particularly attractive within its range of capability. For general use, gas blasting is not likely to be a serious competitor to conventional explosives. It is incapable of primary fracturing in hard rock, the cost of explosive energy is high, and shothole requirements are at least equal to those for chemical explosives. However, it might be possible to make a useful tool for fine-grained soils (frozen or unfrozen) by coupling a repetitive gas-blast shell with a vibratory driver. Such a tool could be used to break frozen silt and frozen sand under shallow water, or to displace stiff clays.

"Explosive rippers" using gas-blasting systems have been considered for working "dry-land" permafrost. The idea is to place a gas-blaster discharge port at the tip of the ripper tooth to assist the fracture process. An experimental device tested in Alaska by CRREL proved disappointing. The discharge pressure of a gas-blaster is too low to induce a shock wave that can create primary fractures in rock, and there is inadequate confinement of the gas bubble at the tip of an operating ripper. However, in an underwater application the gas bubble would be confined, and it might be useful for displacing broken material.

The developers of the REDSOD system (Southwest Research Institute) have also developed a gas-blasting ripper known as the FARE (Fuel/Air Repetitive Explosions) ripper.

Novel methods

The label "novel methods" covers a very wide range of concepts, from highly practical ones that are just coming into use for underwater work, to truly exotic concepts that border on the absurd. The following notes cover a representative sample, from devices such as disc saws and ladder trenchers that could be applied immediately in underwater work, to some of the more credible exotics that might conceivably be of interest for long-term research and development.

Disc saws, wheel ditchers and milling drums

Disc saws, wheel ditchers and horizontal-axis milling drums all fall into a category of machines that can be described as "transverse rotation." In principle, they can rotate either downward into the approaching work (climb milling), or upward against the approaching work (upcut milling). In the former case, the rotor tends to be self-propelling, but it also tends to climb out of the work unless an adequate reaction is provided. In the latter case, the rotor has to be thrust along in the direction of travel, and the rotor may have either positive or negative reaction in the vertical direction. In practice, upcut milling is almost always used (planing can be an exception). In upcut milling, the teeth on the rotor enter the work with almost zero chipping depth, and usually leave the work with maximum chipping depth. Cuttings are transported upward.

Large diameter disc saws have been developed for cutting concrete, asphalt, some rocks, and frozen soils. In the U.S., disc diameters range up to about 7 ft, while in the Soviet Union, where the primary interest seems to be in cutting frozen ground, diameters range up to 3 m (9.8 ft). Kerf widths are in the range 3.5 to 10 in. Maximum cutting depth is normally less than the wheel radius.

Disc saws are effective in cutting frozen soils, concrete and some rocks, but tooth wear can be a serious problem. Traverse rates for effective operation are in the range 2 to 17 ft/min. In frozen soils, specific energy is about 4.7×10^3 lbf/in.^{2} for frozen gravel and about 1.8×10^3 lbf/in.^{2} for frozen silt. In a layered pavement consisting of asphalt (4.5 in.), concrete (7.5 in.), and frozen gravel (22 in.), specific energy was measured around 5000 lbf/in.^{2} in a CRREL test. Disc saws can be used to excavate trench by a "kerf and rib" technique, cutting two parallel slots and breaking out the uncut rib between them. Taking the depth to width ratio of the uncut rib as 2, overall effective specific energy can be reduced by a factor of 5.

The problem of tooth breakage and tooth wear on disc saws can be solved, but there are some inherent disadvantages connected with the variable chipping depth.

CRREL has considerable literature and test data on large disc saws.

Disc saws are beginning to be used for underwater trenching and cable laying. A Florida company has developed and operated a disc saw that is capable of burying underwater cables up to 8 in. in diameter in coral and other soft rocks. The maximum depth of cut is 5.5 ft. The saw consists of a trencher-type wheel, with internal peripheral gear drive, and it is fitted with mining

machine bullet teeth. The wheel is carried on a simple sled that is winched along from a surface barge. The wheel drive is hydraulic. Trenching rates are said to be from 5 to 20 ft/min.

A less successful development effort was made by the U.S. Navy. A Vermeer T-600 rock saw was fitted with hydraulic drive and a cable feed shoe, and it was tested in a nearshore cable-laying operation at Midway Island. There were major problems, and the machine was rebuilt for further tests at Kauai, where again there were major difficulties. As far as can be ascertained, this machine was unsuccessful largely because it was not well adapted for the task; there is no reason to believe that the concept was inherently unsuitable. The carrier vehicle was inappropriate for the working environment, and there were mechanical problems in various parts of the system.

Disc saws can certainly be used effectively for underwater cable burying, but they ought to be designed and built for the job instead of being adapted superficially from existing dry-land equipment.

For burial of large diameter pipes it would be possible to use multiple disc saws, but a more direct approach is to cut the trench with a single wide wheel similar to the wheel ditchers that are used on land.

Bucket-wheel ditchers such as those built by Cleveland, Parsons/Koehring, Barber-Greene and Banister are standard items for trenching on land in unfrozen ground. The most sturdily built ditchers can, with adequate power, operate in "dry-land" frozen soils and some of the softer rocks, but so far they have been uneconomical in frozen gravels because of high tooth costs.

In the 1969 TAPS trials near Fairbanks, a heavy wheel cutting 5 ft wide by 7 ft deep was able to maintain 6 ft/min, and achieve up to 8 ft/min in frozen silt. In frozen gravel, advance rates were 2.2 to 2.5 ft/min, with a few instances of 6 ft/min, presumably in weaker patches of ground. The writer analyzed the 1969 results for the Banister H.A.K. trencher, and calculated the following specific energy values: down to 180 lbf/in.^{2} in frozen silt, 660 lbf/in.^{2} for good production rates in frozen gravel, and 240 lbf/in.^{2} for absolute best performance in frozen gravel.

More recent development work has been done by Banister (the Banister 710 cut 6-ft-wide trench to a depth of 9.5 ft in frozen gravel), but detailed test results are not available to the writer. Both Banister and Henuset are building "super ditchers" for burying gas pipeline in arctic Canada. Parsons also built a very big machine, the 520 "Big Inch," which had a 20-ft-diameter wheel. In the Soviet Union, there are trenchers built specifically for work in frozen ground. The ZTR-253 is said to be capable of excavating 1200 m^3/hr (706 ft^3/min). At a specific energy consumption of 180 lbf/in.^{2} (frozen silt), excavation at this rate would call for a wheel power of 555 hp, which is certainly much more than the installed power of the machine. Some Russian reports on frozen ground excavation equipment seem to make claims in the same class as those made by some U.S. salesmen; the "frozen ground" they consider is probably barely frozen silt with low water content.

On present evidence it appears that the main problem in adapting wheel trenchers for work in hard materials is to design and build more durable cutting teeth. The stressing problem does not appear to be very serious: if we assume an 18-bucket, 14-ft-diameter wheel cutting to 7-ft depth, while turning at 5 rpm and drawing 200 hp, the maximum time-averaged tangential force is 1700 lbf per tooth. This is not a very high value for a large drag bit, but in well cemented coarse gravel there could be high-frequency force fluctuations that might give brief force pulses several times higher than the 1700 lbf mentioned. Nevertheless, it seems quite likely that abrasion on the relief face could present the main bit problem. Two factors seem important in designing better teeth: 1) the teeth should be as large as is reasonably possible, ideally larger than the coarsest fraction of the gravel particles, and 2) the teeth should have *properly designed* hard tips that are oriented, supported, and bonded in accordance with the resultant cutting force and the tooth trajectory through the work.

Another way to make wide cuts in hard material is to use a milling drum of relatively small diameter. Milling drums that rotate about a horizontal axis are currently being used to grade, plane and excavate asphalt and concrete pavements. A drum miller of this type was tested in frozen ground, and the specific energy consumption was estimated as 720 lbf/in.^{2} for frozen silt and 1310 lbf/in.^{2} for frozen gravel. The heavy planing bits fitted to the drum suffered considerable damage and wear in frozen gravel, but test results were sufficiently encouraging to warrant design of an experimental attachment for

military construction machines. Another drum miller was tested for deep cutting of pavements. It had overall specific energy consumption of about 1700 lbf/in.² and process specific energy of about 700 lbf/in.².

A milling drum developed at CRREL as a permafrost excavating attachment for heavy bulldozers consisted of a powered drum, 12 ft long and 5 ft in diameter (across the cutters). Two hydraulic motors, rated at 200 hp, were mounted inside the drum. Drum bearings and end mounts were recessed to permit cutting to more than the drum radius. The drum could be reversed end-for-end to permit either climb milling or upcut milling. Cutting teeth were heavy carbide-tipped tools designed for use on rock tunneling machines. The machine had process specific energy of about 1700 lbf/in.² in frozen gravel and 1500 lbf/in.² in frozen silt. The tooth pattern was not completely satisfactory, and actual power density was too low.

Underwater trench could be cut by a single horizontal axis milling drum, or by a staged sequence of milling drums. However, a drum machine would not be very suitable for trenches narrower than about 18 in.

Design principles and performance data for all kinds of transverse-rotation machines are given in detail elsewhere (Mellor 1975, 1977).

Ladder trenchers and chain saws

Ordinary chain-type trenchers (ladder trenchers) are used mainly for digging in unfrozen soils to depths of 6-8 ft (1.8-2.4 m), with trench widths of 4 to 24 in. (0.1 to 0.6 m). The largest soil trenchers are the chain-bucket types, that can dig to depths of 25 ft (7.6 m) with trench widths up to 6 ft (1.8 m). In order for these machines to operate in harder materials, such as frozen soils, they have to be fitted with special belts, known as "frost chains." Frost chains usually carry rock-cutting drag bits with carbide tips, and they are usually quite narrow, say 8 in. (0.2 m) or less.

On typical ladder trenchers, the cutting side of the chain is usually carried on widely spaced rollers, and the ladder frame is not a very robust structure. Thus for the cutting of hard materials, there is usually a switch to a chain saw machine, on which the chain is continuously supported by a rigid bar.

The most common type of heavy chain saw is the coal cutter. The bar of a coal cutter usually produces a kerf about 6 in. (0.15 m) wide, and it can penetrate to 9, 11, 14 or more feet (up to 25 ft). A variety of hardened or carbide tipped bits are mounted on the chains. Coal cutters have been used for work in rock salt, potash, shale, slate, frozen soils and ice.

Some very large chain saws have been built for special jobs. During construction of the Dallas-Fort Worth Regional Airport, a contractor built a heavy shale saw that could dig to a depth of 22 ft (6.7 m). The saw was mounted on the boom of a hydraulic backhoe, using a wheeled carriage to provide stability and depth control. It traversed at 0.5 ft/min (0.15 m/min).

Some very big chain saws were built for burying a 10-in. gas pipeline in Alaska. The machines, the BorTunCo Roc Saws, have a very heavy chain that cuts an 18-in.-wide (0.46 m) kerf to a depth of 8 ft (2.4 m). The machines work very well in frozen fine-grained soils and in fine gravel, but they have had difficulties in bouldery ground.

Special saws have been built for cutting harder rocks, such as limestone and marble, in quarries. These cut a narrow kerf (about 1.5 in., or 40 mm), and have bars up to about 10 ft (3 m) long. Cutting rates are rather low — around 1 in./min (25 mm/min).

Ladder trenchers or heavy chain saws can probably be used successfully underwater, and for some special purposes they may well be more suitable than most other devices. CRREL outlined a preliminary design for a chain saw trencher as part of a study on undersea cable burial systems made for the Naval Facilities and Engineering Command, U.S. Navy (Mellor et al. 1977). Design principles and performance data for chain-type machines are given in detail elsewhere (Mellor 1976, 1978).

Repetitive impulse devices

For very strong rocks, it is usually impractical to consider cutting by parallel-motion tools (with the exception of diamond tools). The alternative is to use normal-indentation cutting tools. For undersea trenching, normal-indentation tools that require large static reactions are not likely to be suitable, so that leaves inertial systems, such as percussive drills, hammers, or impact breakers.

Repetitive-impulse power tools range from "thunkers," which give a heavy blow at low frequency (e.g. piling hammers), to "buzzers," which give a small-amplitude vibration at high

frequency (e.g. vibratory drivers). They can be grouped for convenience according to frequency: low frequency (of the order of 1 Hz), medium frequency (of the order of 10 Hz), and high frequency (of the order of 100 Hz or possibly higher). Because power is given by the product of frequency, force and amplitude, typical units of moderate size have an inverse relation between frequency and blow energy. Blow energy is usually of the order of 10,000 ft-lbf or more for lower frequency units, of the order of 100-1000 ft-lbf for mid-frequency units, and of the order of 20 ft-lbf or less for high frequency units.

Low frequency tools are represented mainly by powered piling hammers driven by steam, compressed air, or internal combustion. Medium frequency tools are represented by impact breakers powered by hydraulics, compressed air, or direct mechanical action (with springs). High frequency tools are represented by relatively novel vibratory devices in which the primary excitation is usually by rotating eccentric mass or electromagnetic vibration, possibly coupled to the driver through a hydraulic transfer medium. All of these types have been used for breaking, drilling or pile-driving in frozen ground, but quantitative results suitable for analysis are not available.

It has been suggested that there is a minimum level of blow energy below which rock cutting becomes ineffective. Values that have been put forward as practical minima include 280, 750 and even 5000 ft-lbf per inch of cutting edge. These values are highly questionable, and indeed the whole notion seems overly simplistic. However, there may be enough validity to steer the present consideration away from very high frequency devices that develop very small blow energies. This is not to completely rule out vibratory machines. The Sonico (Bodine) BRD-100 and BRD-1000, and the Gardner-Denver "Blowtorch" have been used for drilling and driving, and there is a good deal of experience with the BRD machines in frozen ground.

Percussive rock drills develop a maximum blow energy of about 300 ft-lbf, while small hand-held pavement breakers give up to about 100 ft-lbf. Frequencies are usually less than 1000 blows/min, and a pneumatic rock drill cannot normally deliver more than about 5 hp at the bit. However, this represents a fairly high power density — about 100 hp/ft^2 with a 3-in. bit.

Grantmyre and Hawkes (1975) give blow energies for a large number of boom-mounted hammer impactors. The values range from 125 to 20,000 ft-lbf (low frequency pile drivers deliver up to about 850,000 ft-lbf). Corresponding frequency data are not immediately available, but machines with a blow energy of about 1000 ft-lbf can be expected to run at 300 to 600 blows/min, while heavier machines run more slowly. For example, the Koehring RB8 runs at 225 blows/min with a 4400-ft-lbf blow.

Looking at output power and mechanical efficiency, the last named machine puts out 30 hp maximum, while requiring a 200-hp input to the compressor. A hydraulic impact breaker used by the writer (IR Hobgoblin) delivered up to 12 hp at the tip for a 78-hp diesel input. On pneumatic percussive rock drills it is quite common to require 40-hp input to the compressor for a 4-hp output at the bit. Thus the mechanical efficiency of these systems is of the order of 10% to 15%.

We can make a rough estimate of the amount of power that might be needed to cut a 12-in.-wide trench to a depth of 3 ft. Taking 100 hp/ft^2 as the required power density, about 300 hp would have to be delivered by the cutter. This would call for an input power of 2000 hp or more.

Some of the design limitations of repetitive impulse devices can be overcome by projectile impact breakers. These may employ either a reusable captive projectile, or else free projectiles. A high speed projectile impacting normally on a solid target creates a high stress level. With relatively incompressible projectile and target materials, the initial impact stress is given to a first approximation by ϱcv, where ϱ is material density, c is acoustic velocity for the material, and v is impact velocity.

A simple example is provided by the so-called REAM system, which was developed with funding from the Advanced Research Projects Agency. This system was intended to drive tunnels in hard rock by firing concrete projectiles from a 105-mm howitzer.

There have also been proposals for "missile miners" that fire continuous streams of projectiles, and CRREL studied a proposal for excavating permafrost by firing steel shot or pea gravel from an eductor-ejector.

The writer analyzed this proposed scheme, plotting input data for a wide range of projectiles, from bullets to bombs, and finding a linear correlation between crater volume and projec-

tile energy For impact on frozen soils at velocities up to 4000 ft/s, specific energies were in the range 350 to 3500 lbf/in.[2] In this study, specific energy did not vary systematically with impact energy, or velocity, although for rocks in general there is supposed to be a decrease (improvement) in specific energy as impact energy increases. The CRREL analysis brought out the point that energy has to be developed more by velocity than mass; otherwise, the volume of projectile material thrown against the working face becomes comparable to the volume of material broken out.

For underwater cutting, projectiles would probably have to have the water cleared from their flight path by compressed air. Alternatively, solid particles might be entrained in a high velocity water jet.

Grantmyre and Hawkes (1975) give blow energies for some captive-projectile impact breakers, the values ranging from 3000 to 72,000 ft-lbf These machines do not seem to have gained much acceptance in the commercial sphere.

In the Soviet Union, Zelenin made a major study of frozen ground excavation nearly 20 years ago, carrying out some experiments with drop-wedges. Machine designers seemed to take these tests rather literally, and fitted tractors with frames that allowed a heavy wedge to be winched up and dropped onto frozen ground. It is hard to take these contraptions seriously, but if the idea were to be developed it is possible to imagine a diesel piling hammer hitting a wedge with 30,000 ft-lbf at about 1 blow/s (55 hp), breaking 25 to 31 ft³/min in frozen silt and 9.3 to 13.2 ft³/min in frozen gravel.

For many years there has been interest in vibrating rippers and percussive rippers, and several equipment manufacturers have pursued long-term development projects. One major line of rippers has heavy rubber blocks that are claimed to give a vibrating action; these actually create a complaint system that releases strain energy *after* peak stress and yield has been achieved, and probably do not achieve the basic aim of reducing plowing force. There are on the market eccentric-mass vibrating cable plows, such as the Parsons/Koehring Saberplow DP-100, that are used by utility companies. One New England company begins spring operation in frozen ground with this device, but has to tow the plow vehicle with a surplus M-41 tank, suggesting that the vibration confers little benefit in hard ground One way to make a repetitive-impulse ripper with limited development resources would be to embody a mid-frequency impact breaker in the tooth A deep water undersea cable plow that utilizes vibration has been developed by the U S Navy Civil Engineering Laboratory

One of the main attractions of repetitive-impulse devices is that they require very little bias force to be applied externally, and this could be a significant advantage in underwater work. On the other hand, if experience in surface excavation gives any indication, the general operating characteristics of impactors are not very appealing except in very hard brittle material.

High pressure water jets

The water jets that are used to cut hard materials usually employ nozzle pressures in excess of 10,000 lbf/in.[2] If they can be made to cut rock effectively, high pressure water jets have certain potential advantages over rigid tools. The jet is a non-contact device, and it suffers relatively little wear. Reaction forces on the device are also quite small, so that it is not necessary to transmit high forces. However, jet cutting is very inefficient in energetic terms, so that large amounts of power may be required.

The cutting of materials with high pressure water jets is a relatively new technology that has developed quite rapidly. A good introduction to the field is provided by the Proceedings of the First, Second and Third International Symposiums on Jet Cutting Technology (Coventry, England, 1972; Cambridge, England, 1974; Chicago, Illinois, 1976), and by the proceedings of a National Science Foundation Workshop held in 1975. Two broad development approaches have been followed in jet cutting technology: 1) continuous jets, and 2) discontinuous, or pulsed, jets. Pumps capable of providing continuous jets are currently available from commercial sources with delivery pressures up to 70,000 lbf/in.[2] for small units (around 60 hp), and up to 20,000 lbf/in.[2] for large units (600 to 1200 hp). CRREL worked (through a contract arrangement) with a 200-hp unit that had a pressure capability of 100,000 lbf/in.[2], but it was incapable of continuous operation. Pulsed jets, which even after many years are still in the development stage, are generated by impact

systems, and they can achieve exit pressures of the order of 10^6 lbf/in.^{2}

In the research area, there have been two distinct schools of thought on water jet applications. One holds that intermittent ejection of slugs of water at very high velocity provides the most efficient attack, while the other maintains that continuous jets at the highest feasible pressure level are likely to be the most effective. There might also be a compromise approach involving modulation of continuous jets over a modest amplitude. There is no doubt that in some applications it may be desirable to emphasize velocity over mass in the generation of jet energy (cf. projectile impact), since there are situations where it is inconvenient to supply and remove large volumes of water, e.g. in winter excavation of "dry-land" permafrost, or in underground work. However, when spurious boundary effects are eliminated there is, as yet, little convincing evidence that specific energy consumption decreases significantly with increasing impact velocity, either for typical rocks or for frozen soils and ice. This fact, taken in conjunction with the rapid development of high pressure pump technology, suggests that continuous jets may be more attractive than discontinuous jets for short-term development goals. Another factor is that continuous jets appear to be better adapted for deep penetration, which is very important in most practical applications.

In the continuous jet development field, there has been a tendency to pursue ever higher discharge pressures, in the belief that efficiency improves with increasing pressure. However, there is very little evidence, either experimental or theoretical, to support this quest. On the contrary, there are some indications that, provided water volume is not a consideration, there may be an optimum pressure for a given combination of other variables and rock type. The design goal, therefore, is to estimate an optimum combination of nozzle parameters that is practically feasible.

CRREL investigations have covered the development of design schemes quite thoroughly, taking both theoretical and experimental approaches. This work has been published, and need not be described here. One paper gives a large amount of experimental data for rock cutting (Harris and Mellor 1974).

On the basis of previous experience and available data, it is felt that a jet plow could not be designed for work in hard rock without appreciable development effort, and even then the power demands might well be prohibitive. For initial design estimates, we might suppose that a jet working at some realistic pressure (say 20,000 lbf/in.^{2} for sea water in high power pumps) could penetrate about 15 nozzle diameters at a useful traverse speed. The problem might be to assist a ripper while keeping penetration demands as low as possible. One approach would be to have jets working as "gauge cutters" for a staged series of ripper teeth. One pair of jets would point upward from the edges of the ripper tip, while another pair of jets pointed downward from the top surface of the material. Any one ripper tooth would only work a limited depth — a following ripper would deepen the slot. However, the power demands for such a system quickly become exorbitant.

Figure 10 gives a graphical display of power and flow rate as functions of nozzle pressure and nozzle diameter. More directly, the hydraulic horsepower of a nozzle is $0.0174\, d^2 p^{3/2}$, where d is nozzle diameter in inches and p is nozzle pressure in lbf/in.^{2}

If it is necessary to penetrate 6 in. in a single pass, a first guess is that the required nozzle size for weak rocks might be around 0.4 in. To run a 0.4-in. nozzle at 20,000 lbf/in.^{2}, the required hydraulic power is 7874 hp. For a 3-ft-deep trench, there might be a requirement for 12 nozzles, and a total of 94,500 hp.

This sort of power demand could probably be reduced by clever design and development effort, but the prospects for an efficient system do not look good.

One other type of jet that might be mentioned is the cavitating jet, which works on different principles. The U.S. Navy has apparently developed an interest in use of cavitating jets for underwater trenching, but it seems unlikely that a practical system could be produced in the near future.

Flame jets and plasma torches

High velocity flame jets, such as the Linde torch or the Browning burner, are used for cutting some types of rock, and periodically there are suggestions that they should be used for drilling and cutting frozen ground. CRREL has used Browning burners for drilling and slotting frozen ground, but the performance has been uninspiring.

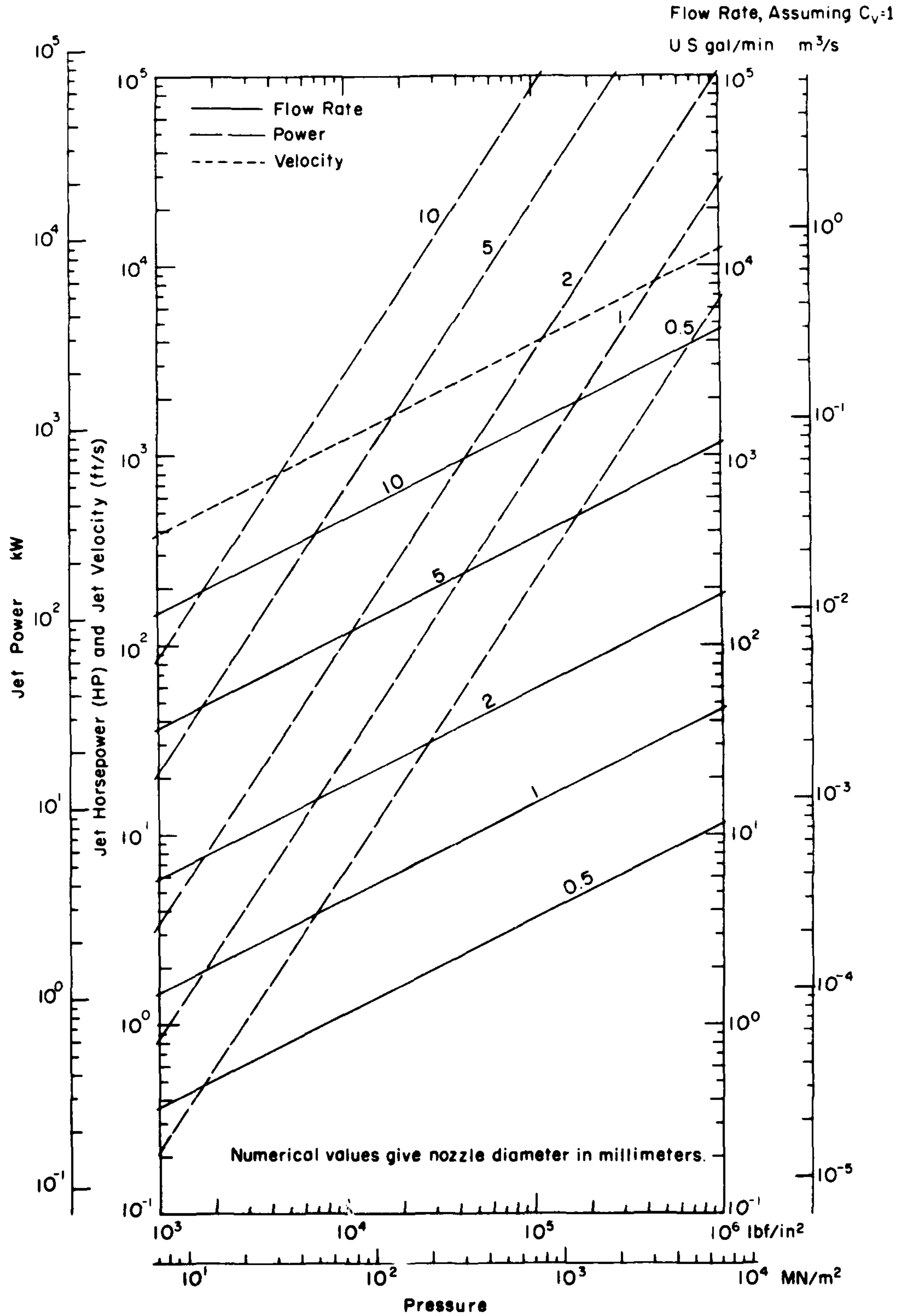

Figure 10. Jet power and flow rate as functions of nozzle pressure and nozzle diameter for "high pressure" water jets.

The rocks that are cut successfully with flame torches are so-called "spallable" rocks, usually crystalline rocks with high density, high modulus, and high quartz content. The torch spalls pieces off the rock surface by inducing thermal strain discontinuities at high rates (the volume expanison coefficient for crystalline quartz is three times greater than for other common constituent minerals), and the jet velocity is sufficient to clear chips from the working surface.

Production rate data are not immediately available for flame jets in rock, but watching the progress of a flame jet channeling operation in a granite quarry is a bit like watching the grass grow. There is a possibility that rock spalling might be enhanced underwater by rapid quenching, but it is hard to imagine an effective trenching tool based on torches.

High temperature heaters have been developed with the intention of boring and tunneling in rock. Power densities of the Los Alamos "Subterrenes" were in the range 0.3 to 2.5 MW/m² (power densities for thermal ice drills are about the same — up to 3.5 MW/m²). However, the practical usefulness of these rock-boring devices still has to be demonstrated.

Ice-bonded soils do not spall; although ice has an expansion coefficient much higher than the silicate soil grains, it is impossible to heat it rapidly through the 100°C or so that would be necessary to provide the required internal strain differentials. Thus a flame torch cuts frozen soils by melting the ice cement, and then blasts the separated particles clear of the working face.

Even a very efficient melting process can be expected to be at least 30 times less efficient in energy terms than typical mechanical cutting, but rough estimates of specific energy for flame torches in frozen ground give values of the order of 10^5 lbf/in.², i.e. about 100 times less efficient than mechanical cutting. This is not surprising, since much of the heat is dissipated by convection to the surrounding air.

Perhaps of more consequence is the inherent rate limitation of a melting process that depends on heat conduction through the solid. During drilling tests with the Browning burner, penetration rates for 6- to 9-in.-diameter holes in frozen silt were from 0.4 to 1.1 ft/min, and 1-ft-diameter hole was produced in frozen gravel at rates up to 3 ft/min. On the basis of these results, it is estimated that one burner of typical size might be capable of advancing the equivalent of 6-ft-deep slots at rates up to 0.14 ft/min in frozen silt and up to 0.5 ft/min in frozen gravel. However, operational slotting results obtained by CRREL did not give rates as high as these.

Flame jets could operate under water of moderate depth, but they do not appear attractive, even though they constitute "zero force" devices.

Electric-arc plasma torches are being developed for metal-cutting and other purposes and it has been suggested that they might be used for excavation. In the present context they can be regarded as being in the same category as flame jets, but because they are of even higher potential they will probably be less efficient.

Electrical discharge and electromagnetic radiation

Electrical and electromagnetic concepts for excavation of rock or frozen ground have not yet developed into realistic practical methods, nor are they likely to do so in the near future (investigators in the USSR might disagree). Nevertheless they tend to attract attention periodically, and for the sake of completeness a few notes are included here. More thorough coverage is given in a CRREL report on the subject (Hoekstra 1976).

Electrical discharge. Electrical discharge methods for breaking rock or frozen ground involve either abrupt dc discharge of energy stored in a bank of capacitors, or else high-loss, high-frequency ac discharge between implanted electrodes. The former is the basis of the electrohydraulic technique for breaking rock and generating underwater shocks. The latter dissipates heat rapidly along preferred conduction paths, which would probably be ice/silicate interfaces in frozen soils, or wet internal surfaces in ordinary rocks. At the present time these techniques do not appear attractive even on a laboratory scale, and there are numerous objections to practical applications in the present content.

Electromagnetic radiation. The logical way to use electromagnetic radiation for breaking rock or frozen ground is to dissipate energy inside the ground material so as to create internal fractures or to destroy ice bonds by partial or complete melting. In broad terms, attenuation of radiation in the ground can be expected to decrease as frequency decreases and wavelength increases. The goal is to find a frequency range which will provide suitable penetration while keeping dissipative power density at a useful level. Obviously,

radiation at optical frequencies will not penetrate at all, while very low frequency signals will penetrate too easily. One might guess that a suitable range would be where the wavelength is about an order of magnitude greater than the maximum grain size of the soil. If a suitable frequency could be found, the radiation might be beamed into the ground at a high power level with a directional antenna. Theoretically, frozen soil should fall apart under these conditions, but the dielectric properties of frozen soils are quite complicated, and prospects for early development of such a device are not good.

The cutting of rock with lasers has evoked considerable interest in recent years, but it is not easy to see why. A beam of coherent light does not suffer geometrical attenuation; it can therefore transmit energy through the atmosphere without much loss, but this is of no great interest in excavation. A focused laser beam can create great power density at a solid surface, giving very high point temperatures. This can cause the surface of "spallable" rock to spall, provided that the beam traverses at a suitable rate. If a focused laser dwells on one point, in either spallable or non-spallable rock, the rock melts, and the molten rock provides an effective barrier to further attack if it is not swept or blown away. In short, a laser does what a flame jet or a plasma torch could do. Laser tests on frozen soils were commissioned by CRREL, but the results were not encouraging.

CRREL also commissioned laboratory tests of electron beam impingement on frozen clay and frozen sand. The resulting specific energy values were in the range 35,000 to 350,000 lbf/in.^{2}, i.e. the process was very inefficient.

On present evidence, electrical and electromagnetic methods have not much to offer for underwater trenching in the short term.

Chemical methods

In principle, there ought to be chemical methods for loosening rocks to permit excavation and pipe burial. One patent was found that described a chemical method for burying underwater pipelines in clay. However, during conversations with the inventor, who was contacted on another matter, it became clear that he did not regard the chemical method as having any practical value.

Conclusions

The imperatives for cable and pipeline burial may be stronger in polar waters than in most other places because of special environmental hazards. The intrinsic problems of subsea trenching are no greater in polar waters than elsewhere, although there are unusual conditions that could complicate operations.

A wide range of existing techniques can be applied in the relatively shallow coastal water where protection needs are greatest, at least in soft bottom materials. However, trenching in hard bottom is inherently difficult in any part of the world. In fact, trenching in hard ground is difficult and expensive even on dry land.

A number of exotic concepts are potentially applicable to subsea trenching, but for the most part they are untried in the underwater environment. For the short term, it would be safer to pass over the exotic concepts and concentrate on progressive development of proven techniques.

In facing excavation problems, some federal agencies and military organizations tend to seek a universal device that does all things under all conditions. While this approach may be warmly endorsed by research entrepreneurs, it is unrealistic. For subsea trenching, as for other construction work, it is more practical to use a variety of tools and techniques to suit the special conditions.

Literature cited

Brown, R.J. (1972) Pipelines can be designed to resist impact from dragging anchors and fishing boards. Paper no. OTC 1570, Offshore Technology Conference, Houston.

Brown, R.J. (1973) Pipeline design to reduce anchor and fishing board damage. *Transportation Engineering Journal, Proceedings ASCE*, vol. 99, no. TE 2.

Grantmyre, I. and I. Hawkes (1975) High energy rockbreaking. *Canadian Mining and Metallurgical Bulletin*, July, p. 1-8.

Harris, H.D. and M. Mellor (1974) Cutting rock with water jets. *International Journal of Rock Mechanics and Mining Sciences*, vol. 11, p. 343-358.

Hoekstra, P. (1976) Rock, frozen soil and ice breakage (sic) by high-frequency electromagnetic radiation — A review. CRREL Report 76-36, 17 p.

Hopkins, D.M., P.W. Barnes, N. Biswas, J. Cannon, E. Chamberlain, J. Oygas, W. Harrison, A.S. Naidu, D. Nummedal, J. Rogers, P. Sellmann, M. Vigdorchuck, W. Wiseman and T. Osterkamp (1977) Synthesis of earth science studies for the Beaufort Sea.

Huston, J. (1970) *Hydraulic dredging*. Cornell Maritime Press, Inc., Cambridge, Maryland, 318 p.

Koehring Company (1975) Estimating manual for hydraulic excavation. Koehring Company, Milwaukee, Wisconsin, 155 p.

Kovacs, A. (1972) Ice scoring marks on the floor of the arctic shelf. *Oil and Gas Journal*, vol. 70, no. 43.

Kovacs, A. and M. Mellor (1974) Sea ice morphology and ice as a geologic agent in the southern Beaufort Sea. In

The coast and shelf of the Beaufort Sea (J C Reed and J E Sater, editors). Arctic Institute of North America, p 113-161

Mellor, M (1975) Mechanics of cutting and boring, Part I Kinematics of transverse rotation machines CRREL Special Report 226, 27 p

Mellor, M (1976) Mechanics of cutting and boring, Part III Kinematics of continuous belt machines CRREL Report 76-17, 24 p

Mellor, M (1977) Mechanics of cutting and boring, Part IV Dynamics and energetics of parallel motion tools CRREL Report 77-7, 85 p

Mellor, M (1977) Mechanics of cutting and boring, Part VI Dynamics and energetics of transverse rotation machines CRREL Report 77-19, 36 p

Mellor, M (1978) Mechanics of cutting and boring, Part VIII Dynamics and energetics of continuous belt machines CRREL Report 78-11

Mellor, M., R Liston, D Garfield and H Ueda (1977) Undersea cable burial system CRREL study for Ocean Engineering Dept., Naval Facilities and Engineering Command, U S Navy, CRREL Internal Report 528 (8 parts), unpublished

Pelletier, R E and J M Sheaver (1972) Sea bottom scoring in the Beaufort Sea of the Arctic Ocean 24th International Geological Congress, section 8

Rockwell, P K (1975) Deep ocean cable burial concept development Technical Report, USN Civil Engineering Laboratory, Port Hueneme, California

Valent, P J and R L Brackett (1976) A comparison of installation and protection techniques for nearshore electrical cables Technical Note N-1428, USN Civil Engineering Laboratory, Port Hueneme, California

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Mellor, Malcolm

Undersea pipelines and cables in polar waters / by Malcolm Mellor. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1978.

v, 36 p., illus., 27 cm. (CRREL Report 78-22.)

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Bibliography: p. 33.

1. Cables. 2. Construction. 3. Electric cables. 4. Engineering. 5. Excavation. 6. Explosives. 7. Operation. 8. Pipelines. 9. Polar regions. 10. Tools. 11. Transmission lines. 12. Underwater. 13. Underwater communications. 14. Underwater equipment. 15. Underwater explosions. 16. Underwater tools. 17. Underwater vehicles. 18. Work. I. United States. Army. Corps of Engineers. II. Series: Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. CRREL Report 78-22.